ANL/EES-TM-334, Vol. 1

SOLID WASTE LEACHATE DATA REVIEW

VOLUME 1: SUMMARIES OF FLUIDIZED-BED COMBUSTION AND FLUE-GAS DESULFURIZATION RESEARCH PROGRAMS

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by

G.M. Kaszynski and S.T. Helm

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FOREWORD

Argonne National Laboratory is reviewing research programs addressing the characteristics of leachates produced from solid wastes generated by fossil fuel technologies. This report covers the characteristics of solid waste leachates from fluidized-bed combustion and flue-gas desulfurization. Subsequent volumes are to review documented data and information on the solid waste characteristics of fly ash and other wastes produced from coal combustion, gasification, and liquefaction, as well as from oil and natural gas technologies.

The project manager for this work is Nancy Johnson of the Division of Planning and Environment in the Office of Fossil Energy.

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ABSTRACT

Solid waste leachate data were compiled for research programs on fluidized-bed combustion (FBC) and flue-gas desulfurization (FGD). The research programs were sponsored primarily by the U.S. Department of Energy, the U.S. Environmental Protection Agency, and the Electric Power Research Institute. The resulting matrices present essential administrative information (sponsoring entity, technical coordinator, research period, etc.) and specific research data derived from research program documentation (waste type, site locations, constituents analyzed, sample size, results, etc.). Based on various leachate extraction procedures, including the EP (extraction procedure) toxicity test, the results suggest that leachates from FBC and FGD solid wastes would not be considered hazardous for the sites examined given the Resource Conservation and Recovery Act (RCRA) limit of 100 times the maximum contaminant level for the eight RCRA trace elements (As, Ba, Cd, Cr, Pb, Hg, Se, and Ag).

1 BACKGROUND

1.1 INTRODUCTION

Many research efforts have resulted in publication of data and information on leachates produced from fluidized-bed combustion (FBC) and flue-gas desulfurization (FGD) solid wastes. This report focuses on investigations that generated baseline solid waste leachate data.

Documented research sponsored by the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), the Electric Power Research Institute (EPRI), and others was reviewed, and selected leachate data were characterized. The research program information was compiled into a series of matrices to determine the breadth of information available and to compare the results of completed projects. For this purpose, certain leachate characterization data were extracted from the research reports. The emphasis was on leachate data obtained via the extraction procedure toxicity (EP Tox) test. However, other leachate extraction procedures and data were included as appropriate.

1.2 DATA SOURCES

Three computerized data bases were searched to identify research programs that had developed data on solid waste leachates from FBC and FGD. A keyword search of DOE's *Research in Progress* (RIP) data base identified 83 potentially applicable research programs. (Additional documentation of DOE-sponsored research programs was obtained by reviewing the monthly publication entitled *Energy and the Environment*, which is published by the Office of Scientific and Technical Information at Oak Ridge National Laboratory.) The second data base, the *Electric Power Data Base*, maintained by EPRI, yielded approximately 132 research programs. Both of these data base searches covered the period from January 1975 through January 1985. The keywords used were waste, solid waste, solids characterization, analysis, chemical analysis (EPRI only), and evaluation (EPRI only).

The *Energy Data Base* (EDB) available through DOE/RECON was also searched. This third data base covers DOE research as well as that of other federal agencies, including EPA. The keywords used were coal, leachates, mining, chemical analysis, fly ash, coal combustion, liquid wastes, and solid wastes. This search produced 166 entries covering the period January 1975 through May 1986. The results confirmed that a comprehensive review of data sources had been achieved.

The three data bases are continually updated. If more recent references are needed, it is possible to search only from an earlier cutoff date to the present. Also, ongoing review of the *EPA Publications Bibliography — Quarterly Abstract Bulletin* and EPA Office of Research and Development publications allows updating of EPA-sponsored research efforts.

Review of research program abstracts contained in the DOE RIP, EPRI, and EDB data bases identified research programs that addressed FBC and FGD solid waste leachate characteristics. Copies of reports from the pertinent programs were acquired; from reference lists contained therein, additional research sponsors and programs were identified.

1.3 RESEARCH PROGRAM DATA STRUCTURE

Separate matrices were developed for the FBC and FGD technologies; see Secs. 2 and 3, respectively. Applicable research programs were organized by sponsoring institution. The FBC research was divided into two matrices: DOE-sponsored research and EPA- and EPRI-sponsored research. Similarly, the FGD research was organized into four matrices: work sponsored by DOE, EPA, EPRI, and the Tennessee Valley Authority (TVA) and Western Energy Supply and Transmission (WEST) Associates. The research programs for each sponsor are briefly described in Apps. A and B. Appendix C briefly summarizes the research programs that have addressed in some way the organic constituents of wastes produced by FBC and FGD systems.

The numbered references on pages 30-32 are cited in Secs. 1-4. Each appendix has a separate list of references; those numbers do not correspond with those on pages 30-32.

The information and data contained in each matrix were derived entirely from published reports identified from the data base searches and from report reference lists. Research program documentation extracted from published reports was broadly categorized as either administrative information or research data. Administrative information included such items as the name(s) of the technical coordinator(s) and principal investigator(s), research period, contract number, and principal reference. Types of research data included waste type, site locations, constituents analyzed, analytical procedures, sample size, data format and type, and results. These categories were included in each of the matrices. Sections 1.3.1 and 1.3.2 explain each of the matrix categories.

1.3.1 Administrative Information

Sponsor: The entities providing funding for the research activity are indicated in the table title.

Technical Coordinator (Tech. Coord.): The person affiliated with the sponsoring organization responsible for overseeing the research is given (sometimes indicated in the literature as project manager, project officer, or research correspondent). If available, a telephone number is included.

Principal Investigator (Prin. Inves.): A single name is provided, along with the name of the performing organization or prime contractor. The individual is the person responsible for directing or managing the research. If available, a telephone number is provided.

Research Period: The date (or range of dates) shows how long a research program has been funded and how current the research activity is. In some instances, the beginning date of the research was not available.

Contract Number (Contract No.): The contract number provides the only useful means of correlating the many types of documents (e.g., formal reports and conference papers) that have been generated by a research program. Also, because many principal investigators and associated prime contractors perform research for many sponsors, the contract number is useful for categorizing their research efforts.

Principal Reference (Prin. Ref.): In many instances, more than one deliverable has been generated for a research program. After these documents were collected, the publication most applicable to solid waste leachate characterization and the most recent publication (if different), are listed by their numbers in the references section. The research data included in the tables were derived primarily from the principal references.

Table Number (Table No.): The research results are presented in more detail in this report in the indicated tables. If no table number is given, the original documentation of the research program does not contain data tables.

1.3.2 Research Data

Waste Types: Each fossil fuel technology generates specific types of wastes. The solid wastes that were subjected to a leaching test are specified. If available, the type of coal used as the feedstock is provided.

Site Locations: The source of the analyzed waste material is identified by research or demonstration facility.

Constituents Analyzed: The list includes only those chemical and physical constituents for which data were generated from leachate analysis.

Analytical Procedures: The type of laboratory leachate extraction procedure is indicated. Field study procedures are sometimes described briefly.

Sample Size: The number of leachate samples from the laboratory or field is provided.

Data Type and Format: The data type indicates whether the data are original baseline data or data interpreted from other sources. The data format indicates how the data are presented in the principal reference. Computerized data storage is mentioned, if applicable.

Results: Quotations were extracted from the principal reference. The intent is to quote results that relate directly to conclusions drawn primarily from the results of leachate analysis.

2 FLUIDIZED-BED COMBUSTION

Applicable FBC research programs and their results were reviewed. Research efforts sponsored by DOE, and EPA and EPRI, to characterize FBC solid waste leachates are summarized in Tables 1 and 2, respectively. The individual programs are described in more detail in App. A. Tables 3-10 present data derived from the research programs summarized in Tables 1 and 2. The data are usually compared with the limits set in the Resource Conservation and Recovery Act (RCRA). All sources cited are listed in the references section of this report.

TABLE 1 DOE-Sponsored Research Programs Concerning FBC Leachate Characteristics

Tech. Coord.	R. Letcher, METC	GFETC	R.R. Hall, GCA Corporation, 617-725-5444	R.L. Hanson, Inhalation Toxicology Research Institute
Prin. Inves.	L. Jackson, Western Research Institute	C.M. Thompson, Radian Corporation	D.R. Sears, GFETC	J.J. Kovach, METC
Research Period	1980–1982	-1982	1982	1977–1980
Contract No.	DE-AP20-84LC 00022	DE-AC18-80FC 10200	DE-AC18-81FC 10281	EY-76-C-04-1013; DE-AC04-76 EV01013
Prin. Ref.	1	2	3	4
Table No.	3	4		
Waste Types	FBC waste; fixed FBC material (80% = above waste and 20% = bit fly ash); ash outlet sample	Fly ash from cyclone particulate collection device and fabric filter baghouse	Bed material; fly ash from primary and secondary cyclone and fabric filter	Ash samples before and after three cleanup systems (cyclone 1, cyclone 2, bag filter)
Site Locations	PER boiler, Alexandria Va.; Keystone station, Indiana, Penn.; EPRI's Babcock & Wilcox plant, Alliance, Ohio	GFETC's process-scale FBC, Grand Forks, N.D.	GFETC's process-scale FBC, Grand Forks, N.D.	METC's AFBC, Morgantown, W. Va.
Constituents Analyzed	As, Ba, Cd, Cr, Pb, Hg, Se, Ag	Eight RCRA elements; Al, B, Ca, Cu, Fe, Mg, Mn, Mo, Ni, Na, Sr, V, Zn; SO_4, SO_3, CO_3	Twenty-four trace elements; 16 presented in Ref. 3; Al, Ba, Be, Ca, Cr, Co, Fe, Mg, Mn, Ni, K, Si, Na, Ti, V, Zn	Particulates only, including vapor-phase organics (PAH) and particle-extractable organics (PAH); elemental concentration of particulates documented in separate paper; no leachate analysis
Analytical Procedures	EP toxicity; ASTM leach test	EP toxicity	No leachate analysis; material-balance study of particulates	No leachate analysis; particulate and hydrocarbon emission study to determine toxicological effects
Sample Size	Three FBC samples	Four samples: North Dakota lignite (2), Texas lignite, and Illinois bituminous coal	Samples collected "at periodic intervals throughout the 10-day test program"; North Dakota lignite	Montana Rosebud subbituminous coal; Texas lignite; West Kentucky bituminous coal; Paraho oil shale
Data Type and Format	Baseline; computer-tape storage; tabular, in report	Baseline; tabular, in report	Baseline; tabular in report	Vapor-phase concentration (total) provided; no concentrations by individual compounds; no concentration given for particle-extractable compounds (listing only); tabular, in paper
Results	"No material exam[illegible] in this study would be classified as [illegible]rdous using current RCRA permissible v[illegible] for the EP toxicity test. ... Seleni[illegible]howed the greatest tendency to leach [illegible] both tests but the levels are much be[illegible]e 100x the drinking water standards."	"Maximum concentrations of As and Se in column leachate aliquots from AFBC fly ash from Texas lignite were far above maximum contaminant levels (Table 4-1). ... At least for AFBC fly ash from western coals, some means to control the rate of release of leachate probably will be required at some sites. ... Maximum concentrations of dissolved solids and sulfate in leachate aliquots from western AFBC fly ashes greatly exceeded secondary MCLs for drinking water supplies."	"Emission rates of most elements from the GF FBC are less than 10% of the emission rates from the conventional combustor. Only Ca, Cr, and Mg approach those observed at the conventional combustion site."	"The highest concentrations and greatest variety of vapor-phase organics were found when Montana Rosebud subbituminous coal and Texas lignite were burned. ... Some FBC effluent particles are mutagenic. ... [O]ur data suggested that vapor-phase cleanup of the effluents will be important. The finding of mutagenic activity in extracts of particulate samples from the FBC should serve as an indication of potential health risk."

Acronyms: AFBC = atmospheric fluidized-bed combustion; ASTM = American Society for Testing and Materials; EP = extraction procedure; EPRI = Electric Power Research Institute; FBC = fluidized-bed combustion; GFETC = Grand Forks Energy Technology Center; MCL = maximum contaminant level; METC = Morgantown Energy Technology Center; PAH = polynuclear aromatic hydrocarbons; PER = Pope, Evans, and Robbins; RCRA = Resource Conservation and Recovery Act.

TABLE 2 EPA- and EPRI-Sponsored Research Programs Concerning FBC Leachate Characteristics

Tech. Coord.	D.B. Henschel, EPA	D.B. Henschel, EPA	R.P. Hangebrauck, D.B. Henschel, EPA	D.A. Kirchgessner, J. Milliken, M. Maxwell, EPA	D.M. Golden, EPRI
Prin. Inves.	D.L. Keairns, Westinghouse	P.F. Fennelley, GCA Corporation	K.S. Murthy, Battelle Columbus Laboratories	T.W. Grimshaw, Radian Corporation	A.G. Eklund, Radian Corporation
Research Period	Dec. 1975 - Jan. 1979	Sept. 1975 - June 1976		1980-1984	1983-1984
Contract No.	68-02-2132, 68-02-3110	68-02-1316 Task 15	68-02-2138?	68-02-3103, Program Eleme[illegible]E 825	1260-39
Prin. Ref.	5,6	7	8	9,10,11	12
Table No.	5,6		7	8,9,10	10
Waste Types	Spent sorbent an[illegible] from AFBC and PFBC		Spent bed materials; fly ash	PFBC bed and cyclone mater[illegible]	Bed ash; cyclone ash; baghouse ash
Site Locations	ANL, Argonne, I[illegible] Exxon's miniplant, Linden, [illegible] PER, Alexandria, Va.; METC, [illegible]antown, W. Va.; EPRI's Babcock [illegible] Wilcox plant, Alliance, Ohio; [illegible]ombustion Power Co.; National Co[illegible] Board (England); Battelle Columbus Labs., Ohio		Exxon's miniplant, Linden, N.J.	Exxon's miniplant, Lind[illegible] N.J.; EPRI's Babcock & Wilco[illegible]lant, Alliance, Ohio; Georget[illegible] AFBC, Washington, D.C.	EPRI's Babcock & Wilcox plant, Alliance, Ohio
Constituents Analyzed	Eight RCRA elements; Al, Sb, Be, B, Bi, Ca, Co, Cu, Fe, Mg, Mn, Mo, Ni, Si, Na, Sr, Sn, Ti, V, Zn, Zr; Cl, F, NO_3, SO_4, SO_3; pH; specific conductance; TDS; TOC		Polycyclic organics; no conclusive results available; Al, As, Ca, Fe, Pb, Li, Mg, Ni, Se, Na, V; SO_4; pH	Al, As, Ba, Be, B, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Hg, Mn, Mo, Ni, K, Se, Si, Ag, Sr, Ti, V, Zn; F, SO_4; pH; TDS; TOC	Al, Ba, Be, B, Cd, Ca, Co, Cu, Fe, Li, Mg, Mu, Mo, Ni, P, K, Se, Si, Na, Sr, Ti, V, Zn; Cl, F, SO_4 (plus additional parameters); pH; TDS; electrical conductivity; TIC; TOC
Analytical Procedures	Shake tests (continuous, intermittent); EP toxicity	Estimates of organic compounds, trace elements, inorganic compounds, and particulates from FBC systems	Minimum acute toxicity effluent (MATE); 720-hour shake test	Leachate generation from laboratory batch equilibrium; leachate attenuation from six field cells with disposal media; laboratory columns with six disposal media only	Batch equilibrium
Sample Size	Seventeen FBC samples from eight facilities		Nine sample points from plant	Three hundred sixty leachate samples from laboratory tests; 224 samples from field cells	Thirteen samples each of bed ash, cyclone ash, and baghouse ash
Data Type and Format	Baseline; tabular in report		Baseline; tabular, in report	Baseline; tabular, in report; computerized (SAS)	Baseline; tabular, in report
Results	"[One] EP leachate ... had an average arsenic concentration of 0.94 ppm. ... Chromium concentrations were much higher (0.15-0.4 ppm) in three samples as compared to the other samples. ... Trace-element levels in FBC leachates are low. With only two exceptions, leachates of all FBC residues ... met all existing DWS. ... The potential concerns in FBC residue disposal are the chemical impact of pH, TDS, SO_4, Ca. ... FBC residue disposal will not be an obstacle to commercialization of FBC."		"Polycyclic organic matter in flue gas or other effluents from FBC units do not appear to be health/ecological hazards. ... The results ... do not imply that FBC of coal generates solid wastes of greater or lesser toxicity than other methods of coal combustion. ... None of the primary drinking water standards are exceeded by a factor of 10 by either [spent bed material or fly ash] leachate."	"Cadmium, manganese, sulfate, and TDS appear to be of potential concern with respect to drinking water standards. ... For the Multimedia Environmental Goals (MEGs), Ca, Cd, Co, Ni, K, Ag, and Mn are all of concern. ... RCRA EP performed on all three FBC wastes yielded leachates that did not exceed any RCRA standard."	"The objective of the project was to determine if wastes currently produced at the B&W plant are similar to wastes collected for the EPA study (see #68-02-3103). ... Elemental concentrations in the leachates were the same for 15 species: Al, Ca, Cd, Co, Cu, Fe, K, Li, Mg, Mn, Ni, Si, Ti, V, Zn. The 1983 waste was higher than the 1979 waste leachate in concentrations of B, Ba, Cr, F, sulfate, TDS, TOC. The 1983 was lower in concentrations of chloride, Mo, Sr, and lower pH vs. 12.4)."

Acronyms: AFBC = atmospheric fluidized-bed combustion; ANL = Argonne National Laboratory; DWS = drinking water standards; EP = extraction procedure; EPA = U.S. Environmental Protection Agency; EPRI = Electric Power Research Institute; METC = Morgantown Energy Technology Center; PFBC = pressurized fluidized-bed combustion; PER = Pope, Evans, and Robbins; RCRA = Resource Conservation and Recovery Act; SAS = statistical analysis systems; TDS = total dissolved solids; TIC = total inorganic carbon; TOC = total organic carbon.

TABLE 3 Concentrations of Eight RCRA Trace Elements, L. Jackson, Western Research Institute (mg/L; mean values, except for maximum contaminant level and RCRA limit)

Element	Maximum Contaminant Level[a]	RCRA Limit[b]	EP Toxicity FBC #1	EP Toxicity FBC #2	EP Toxicity FBC #3	ASTM Leach Test FBC #1	ASTM Leach Test FBC #2	ASTM Leach Test FBC #3
As	0.05	5.0	0.0632	0.0848	0.0371	0.0334	0.0039	0.0035
Ba	1.0	100.0	1.565	1.065	1.044	0.353	0.294	0.224
Cd	0.01	1.0	0.0230	0.0087	0.0135	0.0095	0.0033	0.0085
Cr	0.05	5.0	0.1057	0.0524	0.0516	0.1221	0.0335	0.0385
Pb	0.05	5.0	0.1791	0.0640	0.1292	0.0678	0.0305	0.0766
Hg	0.002	0.2	0.0004	0.00021	0.00055	0.00169	0.00023	0.00176
Se	0.01	1.0	0.1849	0.0633	0.0079	0.1713	0.0150	0.0067
Ag	0.05	5.0	0.0368	0.0249	0.0416	0.0143	0.0166	0.0182

[a]Based on Federal Register for 9/13/79, as amended on 9/23/81.

[b]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 1.

TABLE 4 Concentrations of Eight RCRA Elements, C.M. Thompson, Radian Corporation (mg/L; mean values, except for RCRA limit)

Element	RCRA Limit[a]	EP Toxicity N. Dakota Lignite	EP Toxicity N. Dakota Lignite, Limestone Added	EP Toxicity Texas Lignite	EP Toxicity Illinois Bituminous Coal, Limestone Added
As	5.0	0.006	0.006	0.30	0.004
Ba	100.0	0.083	0.225	0.26	0.11
Cd	1.0	0.03	0.03	0.003	0.03
Cr	5.0	0.1	0.01	0.11	0.1
Pb	5.0	0.4	0.4	0.005	0.4
Hg	0.2	0.0005	0.0005	0.0009	0.0005
Se	1.0	0.004	0.245	0.14	0.008
Ag	5.0	0.06	0.06	<0.002	0.06

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 2.

TABLE 5 EP Tox Test Results for FBC Waste Samples, D.L. Keairns, Westinghouse Research and Development Center (mg/L, single values)[a]

Sample	Element							
	Ag	As	Ba	Cd	Cr	Hg	Pb	Se
RCRA limit[b]	5.0	5.0	100.0	1.0	5.0	0.2	5.0	1.0
Battelle bed	<0.02	0.001	<1	<0.01	0.09	<0.0005	<0.04	0.001
Battelle carryover, cyclone	<0.02	0.001	1	<0.005	0.06	0.0007	<0.04	<0.001
MERC carryover, bag filter	<0.02	0.004	<1	<0.005	0.4	0.0008	<0.04	0.01
PER carryover, CBC residue	<0.02	<0.001	<1	<0.01	0.04	0.0007	<0.03	<0.001
Argonne C_2/C_3 bed	<0.02	0.023	<1	<0.01	0.02	<0.0005	<0.04	0.003
Leatherhead carryover, primary cyclone	<0.04	0.002	<1	<0.01	<0.05	0.0005	<0.04	0.007
Leatherhead carryover, 2nd cyclone	<0.04	0.012	<1	<0.01	<0.05	0.0021	<0.04	0.008
Exxon No. 73 bed	<0.04	0.002	<1	<0.01	<0.05	<0.0005	<0.04	0.003
Exxon No. 73 carryover, 2nd cyclone	<0.04	0.002	<1	<0.01	0.06	0.001	<0.04	0.020
Exxon No. 73 carryover, 3rd cyclone	<0.04	<0.001	<1	<0.01	0.35	0.0022	<0.04	0.017
Exxon No. 67 carryover, 3rd cyclone	<0.02	0.007	<1	0.045	<0.02	0.0008	<0.04	0.005
Exxon No. 105 combustor bed	<0.02	<0.001	<1	<0.01	<0.05	0.0006	<0.05	<0.001
Exxon No. 105 regenerator bed	<0.02	<0.001	<1	<0.01	0.15	0.0015	<0.01	0.004
Exxon No. 105 carryover, 2nd cyclone	<0.02	0.68-1.12	<1	<0.01	<0.05	0.0019	<0.05	0.008
Exxon No. 105 carryover, 3rd cyclone	<0.02	0.004	<1	<0.01	<0.05	0.0012	<0.05	0.007
Exxon No. 105 regenerator carryover	<0.02	<0.001	<1	<0.01	<0.05	0.0014	<0.05	<0.001
Combustion power P-403 carryover, baghouse	<0.02	<0.001	<1	<0.005	<0.02	0.0009	<0.04	<0.001

[a]Acronyms: MERC = Morgantown Energy Research Center fluidized-bed combustion unit; PER = Pope, Evans, and Robbins atmospheric fluidized-bed combustion unit; CBC = carbon burnup cell.

[b]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 5.

TABLE 6 Two-Hundred-Hour Shake Test for Selected FBC Units and Parameters, D.L. Keairns, Westinghouse Research and Development Center (mg/L, single values)

		Atmospheric FBC System					Pressurized FBC System		
			Pope, Evans, and Robbins		Battelle		Exxon		
Element	RCRA Limit[a]	Babcock & Wilcox: Carryover	Bed	Carryover	Bed	Carryover	Bed	Carryover	Combustion Power: Carryover
As	5.0	<0.003	<0.002	<0.002	<0.05	<0.05	0.002	0.016[b]	<0.003
Ba	100.0	<1	<1	<1	<1	<1	<1	<1	<1
Cd	1.0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr	5.0	<0.01	<0.05	<0.05	0.05	0.04	<0.05	<0.05	<0.02
Pb	5.0	<0.01	<0.05	<0.05	<0.01	0.05	<0.05	<0.05	<0.01
Hg	0.2	<0.002	<0.001	<0.001	<0.002	<0.002	<0.001	<0.001	<0.002
Se	1.0	<0.003	<0.003	<0.003	<0.01	<0.01	<0.003	<0.003	<0.003
Ag	5.0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80) for EP Tox test only.

[b]Average of two samples.

Source: Data are from Ref. 6.

TABLE 7 Inorganics in Leachates from Bed Material and Carryover Based on the 720-Hour Intermittent Shake Test, K.S. Murthy, Battelle Columbus Laboratories (mg/L; mean values, except for RCRA limit)

Item	Bed	Carryover	RCRA Limit[a]
Li	6	20	--
Na	10.4	52	--
Mg	9.6	6.4	--
Al	0.8	1.4	--
Ca	460	1000	--
V	0.1	0.1	--
Fe	0.2	0.2	--
Ni	0.03	0.03	--
Se[b]	0.07	0.07	1.0
Pb[b]	0.05	0.05	5.0
As[b]	0.04	0.05	5.0
CN^-	<0.03	<0.03	--
SO_4^{-2}	1610	1950	--
pH	12.2	9.0	--

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80), for EP Tox test only.

[b]RCRA elements.

Source: Data are from Ref. 8.

TABLE 8 Laboratory Leachate Generation and Attenuation for Exxon Pressurized FBC Source, T.W. Grimshaw, Radian Corporation (mg/L; mean values, except for RCRA limit)

Item	RCRA Limit[a]	Leachate Generation Protocol Step 1 (mean)	Leachate Attenuation -- Protocol Step 4 (Fig. A.1)					
			Shale	Sandstone	Alluvium	Glacial Till	Limestone	Interburden
As	5.0	<0.08	<0.08	<0.08	ND[b]	ND	ND	<0.08
Ba	100.0	0.171	0.221	0.095	0.233	0.157	0.190	0.116
Cd	1.0	<0.005	0.189	<0.005	<0.005	<0.005	0.024	<0.005
Cr	5.0	0.0597	0.0337	0.054	0.102	0.084	0.124	0.049
Pb	5.0	<0.07	<0.07	<0.07	ND	ND	ND	<0.07
Hg	0.2	ND	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Se	1.0	<0.12	<0.0625	<0.0625	<0.005	<0.005	<0.005	<0.0625
Ag	5.0	<0.005	<0.005	0.029	0.0914	0.078	0.175	0.0093
pH	ND	11.8	10.9	12.0	11.1	9.32	11.9	11.6
TDS	ND	3210	1295	3590	1530	1580	2630	3470

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80), for EP Tox test only.

[b]ND = not determined.

Source: Data are from Ref. 10.

TABLE 9 Comparison of RCRA Limits and Laboratory Extraction Data with Step 1 Protocol Leachate Concentrations, T.W. Grimshaw, Radian Corporation (mg/L; mean values, except for RCRA limit)

Element	RCRA Limit[a]	Exxon PFBC		EPRI/B&W AFBC		Georgetown AFBC	
		RCRA	Step 1	RCRA	Step 1	RCRA	Step 1
Ag	5.0	<0.05	ND[b]	<0.05	ND	<0.05	ND
As	5.0	<0.003	0.04	<0.003	ND	<0.003	ND
Ba	100.0	9.9	11	0.04	3.5	<0.01	0.16
Cd	1.0	<0.05	0	<0.05	0.04	<0.05	0.02
Cr	5.0	<0.1	0.09	<0.1	0.12	<0.1	0.05
Hg	0.2	<0.001	ND	<0.001	ND	<0.001	ND
Pb	5.0	<0.2	0.03	<0.2	ND	<0.2	ND
Se	1.0	<0.003	0.06	<0.003	ND	<0.003	ND

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

[b]ND = not determined.

Source: Data are from Ref. 11.

TABLE 10 Comparison of Leachate Composition Derived from the EPRI/Babcock & Wilcox FBC Plant, T.W. Grimshaw, Radian Corporation (mg/L; mean values, except for RCRA limit)

Item	RCRA Limit[a]	EPA Study	EPRI Study
Al	--	1.0	0.39
B	--	3.5	12
Ba	100.0	0.13	0.55
Ca	--	1340	1400
Cd	1.0	0.04	0.03
Cl	--	51	26
Co	--	0.08	0.06
Cr	5.0	0.12	0.35
Cu	--	0.14	0.11
F	--	0.25	0.66
Fe	--	0.08	0.11
K	--	44	53
Li	--	0.36	0.32
Mg	--	0.81	1.1
Mn	--	0.02	0.02
Mo	--	0.42	0.29
Na	--	13	16
Ni	--	0.11	0.05
Si	--	0.55	0.48
Sr	--	21	11
Ti	--	0.32	0.33
V	--	0.26	0.24
Zn	--	0.04	0.03
pH	--	12.4	11.73
SO_4	--	1110	2433
TDS	--	3780	7600
TOC	--	1.2	40

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Refs. 11 and 12.

3 FLUE-GAS DESULFURIZATION

Solid waste leachates from FGD systems have been characterized in studies sponsored by DOE (Table 11), EPA (Table 12), EPRI (Table 13), and TVA and WEST Associates (Table 14). These research projects are discussed in more detail in App. B. Tables 15-23 present data derived from the research programs summarized in Tables 11-14, as well as from other programs discussed in App. B.

TABLE 11 DOE-Sponsored Research Programs Concerning FGD Leachate Characteristics

Tech. Coord. Prin. Inves.	R. Letcher, 304-291-4666 L. Jackson, Western Research Institute, 307-721-2011	GFETC G.H. Groenewold, University of North Dakota	H.M. Ness, GFETC C.M. Thompson, Radian Corporation, 512-454-4797	H.M. Ness, GFETC C.M. Thompson, Radian Corporation, 512-454-4797
Research Period	1977-1983	1978-1981	1982	1982
Contract No.	AP20-84LC00022	DE-AB18-80FC10120	AC18-80FC10200	AC18-80FC10200
Prin. Ref.	1	13	14	15
Table No.	15		16	17
Waste Types	Lignite scrubber sludge; fixed and unfixed bituminous coal scrubber sludge	Sludge from wet scrubber that uses fly ash in lieu of lime/limestone	Sodium-based spray-dryer and spray-injection wastes	Treated and untreated wet-scrubber sludge; lime and fly ash in varied proportions used as scrubbing reagents
Site Locations	Milton Young power plant, Center, N.D.; Elrama power plant, Washington, Penn. (lignite and bituminous coal)	Milton Young power plant, Center, N.D., after disposal in the Center mine (surface coal mine; low-sulfur lignite coal)	Power plants burning low-rank western coals (location not specified)	Coal Creek power plant, Underwood, N.D.; Milton Young power plant, Center, N.D.; Clay Boswell power plant, Cohasset, Minn.; TVA's Shawnee steam plant, Paducah, Ky. (lignite; western bituminous and eastern bituminous coals)
Constituents Analyzed	As, Ba, Cd, Cr, Pb, Hg, Se, Ag	Al, As, Ba, Cd, Ca, Cr, Fe, Pb, Mg, Hg, Mo, K, Ag, Se, Na; SO_4; TDS; alkalinity	EP toxicity: As, Ba, Cd, Cr, Pb, Hg, Se, Ag; column leaching: Al, As, Ba, B, Ca, Cr, Cu, Fe, Mg, Mo, Ni, Se, Na, Sr, V, Zn; SO_4; SO_3; pH; conductivity; dissolved solids	Al, As, Ba, B, Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Hg, Mo, Ni, Se, Ag, Na, Sr, V, Zn; pH
Analytical Procedure	EP toxicity, ASTM D3987-81	No extraction used; samples obtained directly from groundwater and interstitial water	EP toxicity; column leaching	EP toxicity; column and sequential batch leaching
Sample Size	Three FGD samples tested by 13 laboratories; duplications and quality control samples required	Sixty-nine sample sites for replicate analyses on groundwater from piezometers and interstitial water in area of FGD dry-pit disposal and waste vee-notch disposal	Five samples (one from a sodium-based spray dryer containing lignite ash and four sodium-based dry-injection wastes containing subbituminous coal ash); all samples provided by GFETC	Four sites, each of which sampled for three days
Data Type and Format	Baseline; tabular listing of statistics (complete listing of results available in Ref. 7 of Prin. Ref.)	Baseline; tabular and graphic	Baseline; tabular and graphic	Baseline; tabular; averages for each element and individual analyses
Results	"No material e [illegible] ed in this study would be classified [illegible] zardous using the 100 x MCL as the perr [illegible] le limit. Of the eight metals analyze [illegible], Hg, and Pb showed no tendency to lea [illegible] om the wastes under the conditions of [illegible] test. Se showed the greatest tender [illegible] o leach in both tests [range of 0.058 [illegible] .404 mg/L]."	"This study has demonstrated that water in contact with both the fly ash and fly-ash FGD waste is characterized by very high TDS concentrations. [Highest] FGD sample was 10,351 mg/L]. ... Predominate major species in solution are sodium, magnesium, calcium, and sulfate. Sulfate, lead, and chromium concentrations in waste-affected groundwater are sufficiently high so that the water would be unfit to drink [Pb exceeded 0.1 ppb in two samples]. ... Neither ... waste constitutes a hazardous waste by RCRA [100 x MCL standard]."	"Concentrations of RCRA trace elements in EP extracts indicated that these materials would be classified as nontoxic according to the present EP toxicity test [100 x MCL]. ... Arsenic and selenium were very soluble under dynamic leaching conditions as found in the columns. ... No column leachate aliquots collected during this study had pH values within the acceptable range for public drinking water supplies as specified by the National Secondary Drinking Water Regulations."	"All [illegible] ials tested would be classified as no [illegible] c according to the characteristic of EP [illegible] city [100 x MCL]. ... Use of the natur [illegible] ailable alkalinity of western fly ashes [illegible] FGD systems reduces reagent require [illegible] substantially or eliminates them altog [illegible]. Sludge treatment had variable effec [illegible] leachate quality."

Acronyms: ASTM = American Society for Testing and Materials; EP = extraction procedure; FGD = flue-gas desulfurization; GFETC = Grand Forks Energy Technology Center; MCL = maximum contaminant level; RCRA = Resource Conservation and Recovery Act; TDS = total dissolved solids.

TABLE 12 EPA-Sponsored Research Programs Concerning FGD Leachate Characteristics

Tech. Coord. Prin. Inves.	J.W. Jones R.B. Fling, Aerospace Corporation	J.W. Jones J. Rossoff, Aerospace Corporation	J.W. Jones C.J. Santhanam, Arthur D. Little	C.C. Chatlynne N.C. Mohn, Combustion Engineering, Inc.; R.P. Van Ness, Louisville Gas & Electric
Research Period	Sept. 1974 - June 1978	1973-1977	Oct. 1979 - Nov. 1982	-1978
Contract No.	68-02-2633	68-02-1010	68-02-3167	68-02-2612
Prin. Ref.	16	17 (EPA-650/2-74-037a and EPA-600/7-77-052 are earlier related reports)	18	19
Table No.			18	18
Waste Types	Lime and limestone wet-scrubber sludges mixed with 40% fly ash by weight	Untreated and treated wastes from scrubbers using lime, limestone, and double-alkali processes; with and without fly ash	Stabilized FGD waste and fly-ash/FGD	Lime/limestone wet-scrubber sludges combined with fixative and/or fly ash
Site Locations	TVA's Shawnee steam plant; Paducah, Ky.; eight field disposal sites (two with untreated sludge, three with chemically treated sludge, and three with untreated sludge with underdrainage)	TVA's Shawnee steam plant, Paducah, Ky.; Louisville Gas & Electric's Paddy's Run station, Louisville, Ky.; Gulf Power Company's plant Scholz	Duquesne Light's Elrama plant, Washington County, Penn.; Sherburne County power plant, Sherburne County, Minn.	Louisville Gas & Electric's Paddy's Run station, Louisville, Ky. (3% sulfur West Kentucky coal)
Constituents Analyzed	As, B, Ca, Pb, Mg, Hg, Se, Na; Cl, SO_4, SO_3; pH; alkalinity; COD; conductivity; TDS; TSS	As, Be, Cd, Cr, Pb, Hg, Se, Zn; F, Cl, SO_4, SO_3; TDS; pH; COD	As, Ba, Cd, Cr, Pb, Hg, Se, Ag	As, Ba, Cd, Ca, Pb, Hg, Se; Cl; TDS
Analytical Procedures	Elemental analysis of groundwater, supernate, leachate, underdrain, runoff, sludge, and soil cores	Several methods of column leaching that are study specific; elemental analysis of scrubber liquors	EP toxicity; direct analysis of field samples	Direct analysis of field samples (laboratory analysis performed previously; results in a previous report cited in references)
Sample Size	Samples analyzed (total from eight ponds): supernate - [illegible] leachate - 140, groundwater wells [illegible]), underdrain - 44, and runoff - 14	Three samples; 25 sets of analyses	Wells, waste solids, soils, and waste extracts were tested (three FGD wastes tested using EP toxicity)	Ten sludge/fly-ash mixtures analyzed in the field evaluation; primary leachate and run[illegible]ff [illegible]ampled at 30-day intervals for 720 day[illegible]en liquids were not frozen
Data Type and Format	Baseline; tabu[illegible]and graphic	Baseline and interpreted; tabular and graphic	Baseline and interpreted; tabular (in Part D of Prin. Ref.)	Ba[illegible]e; graphic
Results	"The groundwat[illegible]associated with all ponds show no effec[illegible]tributable to chemically treated or unt[illegible]ed waste disposal. ... Of several thous[illegible]analyses of treated and untreated slud[illegible]eachate, only two showed trace-element [illegible]entrations greater than 10 times the [illegible]vable in drinking water (i.e., one selenium and one cadmium case), and these were in the range of 10 to 20 time the allowable."	"The presence of fly ash in a sludge will cause significantly increased concentrations of only a few trace metals in the liquor or leachate by as much as a factor of 10 over concentrations in the liquor or leachate of a sludge containing no fly ash. ... [R]emoval of fly ash ahead of the scrubber does not eliminate the trace elements from the sludge liquors and leachates, but the concentration levels of some trace elements may be significantly reduced."	"Data from the study suggest that no major environmental effects have occurred at any of the six sites. For example, data from wells downgradient of the disposal sites indicate that the contribution of waste leachate to the groundwater has generally resulted in concentrations of chemicals less than the primary drinking water standards established by EPA."	"I[illegible]l cases, mixture 1 in impoundment 1, a [illegible]compacted mixture formulated using n[illegible]atered sludge, provided the highest c[illegible]trations of trace elements in the l[illegible]ate. It should be noted, however, [illegible]all analytical results were well below [illegible]CRA limits for trace elements [100 x [illegible] ... The concentration of contaminants generally decreased with time from those impoundments where a sufficient number of samples were collected to assess the long-term trend."

Acronyms: COD = chemical oxygen demand; EP = extraction procedure; EPA = U.S. Environmental Protection Agency; FGD = flue-gas desulfurization; MCL = maximum contaminant level; TDS = total dissolved solids; TSS = total suspended solids; TVA = Tennessee Valley Authority

	I.P. Murarka, 415-965-4801 K.V. Summers, Tetra Tech, Inc. 1978-1981 RP1487-12 22	R.Y. Komai, 415-965-4801 J.P. Woodyard, Stearns, Conrad, and Schmidt, Consulting Engineers, Inc., 213-426-9544 Oct. 1979 - April 1980 RP1260-16 23 20
.th	Wet-lime process FGD sludge and calcium-based dry-scrubber waste	Dry FGD waste; more advanced processes (e.g., dry injection and spray drying) emphasized
'VA	Wide variety of locations and coal types	Not available
'k-	As, Ba, Cd, Cr, Pb, Hg, Se, Ag	Al, As, Cd, Cu, Pb, Hg, Se, Na; F, SO_4, SO_3; alkalinity; pH; TDS
ıg, il en	EP toxicity; ASTM long-term batch tests and column tests	EP toxicity; toxicant extraction procedure; five-day shake test
r-	Fifty data points for entire study of all wastes (four EP Tox tests on FGD wastes)	Data presented as one set of ranges for each of the three extractions
c,	Interpreted; tabular and computer-stored	Interpreted; tabular and statistical
he at ly re ne of ds he at	"Available EP extraction test results show trace-element leachate concentrations for Ag, Cr, Hg, Pb, and Se of less than 0.5 mg/L, except for As, Ba, and Cd, which were up to 1.6 mg/L. Few column tests have been run on either fixed or unfixed FGD sludge. When measured, trace-element concentrations in the column leachates were less than 1 mg/L."	"In all of the cases examined, fixed specimen extracts showed lower metal content than the unfixed ones; concentrations of arsenic, cadmium, and selenium were two to five times higher in the unfixed sample extracts. ... The results of the above leaching tests indicated that the metal concentrations in the extracts were a function of the pH and the surface area-to-volume ratio of the solid material. Furthermore, these tests revealed that the particular wastes examined would not be classified as hazardous under RCRA [100 x MCL]."

ıental Protection Agency; EPRI = Electric Power Research Institute; FGD = flue-gas desulfuriza-
ıority.

TABLE 14 TVA- and WEST-Associates-Sponsored Research Programs Concerning FGD Leachate Characteristics

Tech. Coord. Prin. Inves.	J.L. Crowe, TVA, 615-751-0011 J.E. Garlanger, Ardaman & Associates	WEST Associates P. Winkler, Public Service Company of Colorado
Research Period	-1983	-1983
Contract No.	TV-58330A	
Prin. Ref.	24	25
Table No.	22	23
Waste Types	FGD gypsum/fly-ash waste	Dry FGD waste (from spray dryers and dry injection system that use both Na- and Ca-based reagents); with and without fly ash
Site Locations	TVA's Widows Creek power station, Stevenson, Ala.	Public Service Company of Colorado's Arapahoe steam plant, Denver, Colo.; Cameo Steam Plant, Grand Junction Colo.
Constituents Analyzed	As, B, Ba, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Se, Ag, S; CO_3, Cl, SO_4, SO_3; TDS; TOC	As, Ba, Cd, Cr, Pb, Hg, Se, Ag; SO_4, SO_3
Analytical Procedures	EP toxicity; EP toxicity neutral; column leaching	EP toxicity
Sample Size	One site tested using three different methods	Twenty-one waste samples analyzed along with several control samples
Data Type and Format	Baseline, tabular	Baseline; tabular, graphic, and statistical
Results	"Using the EPA extraction procedure (EP) toxicity test, the Widows Creek FGD gypsum fly ash waste was found to lack the characteristics of EP toxicity [100 x MCL]. ... Few relationships were found between the EP toxicity extracts and column leaching test leachate concentrations. For projections of leachate concentrations, the column leaching test data are preferred since the test reasonably models in situ conditions. ... As expected, the deionized water extracts display lower constituent concentrations for most measured parameters."	"The concentration of the metals present in the fly ash/dry-scrubber waste combination was in each case below the EPA toxic limit [100 x MCL] and in many cases below the metal detection limit for the analytical method. The data showed differing degrees of variability amongst the samples for each of the parameters. Some metals as selenium showed a very high variability between the samples, whereas barium and lead showed a consistent below detectability analysis for samples as did mercury and, to some extent, silver."

Acronyms: EP = extraction procedure; EPA = U.S. Environmental Protection Agency; FGD = flue-gas desulfurization; MCL = maximum contaminant level; TDS = total dissolved solids; TOC = total organic carbon; TVA = Tennessee Valley Authority.

TABLE 15 EP Tox Test Data for FGD Scrubber Sludges, L. Jackson, Western Research Institute (mg/L; mean values, except for RCRA limit)

Element	RCRA Limit[a]	Lignite Scrubber Sludge	Bituminous Coal Scrubber Sludge	Bituminous Coal Scrubber Sludge (fixed)
As	5.0	0.0120	0.2862	0.1760
Ba	100	0.188	0.958	1.078
Cd	1.0	0.0058	0.0262	0.0178
Cr	5.0	0.0222	0.0844	0.0606
Pb	5.0	0.0137	0.1540	0.1130
Hg	0.2	0.00044	0.00220	0.00095
Se	1.0	0.0198	0.4165	0.3777
Ag	5.0	0.0115	0.0204	0.0308

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 1.

TABLE 16 EP Tox Test Data for FGD Spent Dry Sorbents, C.M. Thompson, Radian Corporation (mg/L, single values)

		Spray Dryer; Lignite; Sodium	Dry Injection[a] and Subbituminous Coal			
Element	RCRA Limit[d]	Carbonate Sorbent	Trona[b] Sorbent	Trona Sorbent	Nahcolite[c] Sorbent	Nahcolite Sorbent
As	5	0.041	0.019	0.099	0.023	0.078
Ba	100	0.17	0.019	0.016	0.030	0.083
Cd	1	<0.03	<0.03	<0.03	<0.03	<0.03
Cr	5	<0.1	0.1	0.2	<0.1	0.2
Pb	5	<0.4	<0.4	<0.4	<0.4	<0.4
Hg	0.2	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Se	1	0.051	0.006	0.060	0.021	0.068
Ag	5	0.07	<0.06	<0.06	<0.06	<0.06

[a]Average of two concentrations.

[b]Sodium sesquicarbonate.

[c]Sodium bicarbonate.

[d]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 14.

TABLE 17 EP Tox Test Data for Untreated FGD Sludges, C.M. Thompson, Radian Corporation (mg/L; mean values, except for RCRA limit)

Element	RCRA Limit[a]	Coal Creek Station	M.R. Young Station	Clay Boswell Station	Shawnee Station
As	5	<0.003	<0.003	<0.003	0.03
Ba	100	0.6	0.5	0.57	0.5
Cd	1	0.01	0.01	<0.02	0.01
Cr	5	0.39	0.34	0.32	0.3
Pb	5	<0.1	<0.1	<0.1	<0.1
Hg	0.2	<0.004	<0.0005	0.002	<0.0002
Se	1	<0.004	<0.003	<0.003	0.04
Ag	5	<0.002	<0.002	<0.002	<0.002

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 15.

TABLE 18 **EP Tox Test Data for FGD Wastes, C.J. Santhanam, Arthur D. Little; Engineering Science; and N.C. Mohn, Combustion Engineering, Inc., and R.P. Van Ness, Louisville Gas & Electric (mg/L; mean values, except for RCRA limit)**

Element	RCRA Limit[a]	Three FGD Grab Samples (Ref. 18)	Untreated Bituminous Scrubber Sludge (Ref. 19)	Treated Bituminous Scrubber Sludge (Ref. 19)	Lignite Scrubber Sludge (Ref. 26)
As	5.0	<0.002-0.065	0.040-1.0	0.005-0.6	<0.0003-0.075
Ba	100	<0.150-0.230	0.2-2.5	0.29-2.5	<0.01-0.78
Cd	1.0	<0.002-0.020	<0.00003-0.063	0.00003-0.041	<0.001-0.01
Cr	5.0	<0.011-0.026	0.04-0.13	0.02-0.11	0.00125-<0.5
Pb	5.0	<0.005	0.0004-0.43	0.0004-0.26	<0.0005-<0.05
Hg	0.2	<0.002	<0.0002-0.0096	0.00004-0.0036	<0.00002-0.0003
Se	1.0	0.008-0.049	0.0015-1.47	0.0015-1.35	<0.002-0.5
Ag	5.0	<0.001	<0.01-0.03	<0.01-0.05	<0.009-<0.04

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Sources: Data are from Refs. 18, 19 and 26.

TABLE 19 EP Test Data for FGD Waste, C.M. Thompson, Radian Corporation (mg/L, single values)

Sample	As	Ba	Cd	Cr	Pb	Hg	Se	Ag
RCRA Limit[a]	5.0	100	1.0	5.0	5.0	0.2	1.0	5.0
Spent solids from nahcolite injection - KVB test facility - Cameo station								
Uncured	0.004	0.33	0.012	0.11	<0.002	<0.0002	0.039	0.019
Cured	0.004	0.21	0.009	0.013	<0.002	<0.0004	0.02	<0.002
Spray-dryer product from spray-dryer hopper - lime only runs - research - Cottrell test facility - Comanche station	<0.003	4.0	<0.0005	<0.005	<0.005	<0.0002	<0.004	<0.01
Spray-dryer product from fabric filter - lime only runs - research - Cottrell test facility - Comanche station								
Uncured	0.004	0.54	<0.0005	0.10	<0.002	0.0005	0.01	<0.01
Cured	<0.003	1.1	0.002	<0.001	<0.002	0.0006	<0.003	<0.002
Spray-dryer product from spray-dryer hopper - sodium carbonate runs - lodge - Cottrell test facility - Four Corners station								
Uncured	0.28	0.67	0.0023	0.12	<0.002	0.0005	0.075	<0.01
Cured	0.26	0.093	0.006	0.02	<0.002	0.002	0.075	<0.002
Spray-dryer product from baghouse - sodium carbonate runs - lodge - Cottrell test facility - Four Corners station								
Uncured	0.058	0.81	0.0044	0.13	<0.002	0.0011	0.23	<0.01
Cured	0.22	0.084	0.007	0.033	<0.002	0.0003	0.20	<0.002
Spray-dryer product from electrostatic-precipitator hopper - sodium carbonate runs - lodge - Cottrell test facility - Four Corners station								
Uncured	0.077	0.56	0.0044	0.089	0.006	0.0009	0.15	<0.01
Cured	0.20	0.065	<0.0005	0.032	<0.002	0.0003	0.065	0.003
Spray-dryer product - Flakt test facility - Jim Bridger station								
Uncured	<0.003	3.1	<0.0005	0.12	<0.005	<0.0002	0.031	0.39
Cured	<0.003	0.78	<0.0005	<0.001	<0.002	0.0006	<0.003	<0.002
Spray-dryer product from baghouse - no recycle - Rockwell International's test facility - Joliet station								
Uncured	0.005	1.0	<0.0005	0.12	<0.002	0.0005	0.068	<0.01
Cured	<0.003	0.52	<0.0006	0.014	<0.002	0.0003	<0.003	<0.002
Cured	<0.003	0.44	<0.0005	0.069	<0.002	0.0006	0.008	<0.002
Spray-dryer product from baghouse and spray-dryer hoppers - pebble lime used as reagent - Strathmore Paper Company								
Uncured	0.005	1.1	<0.0005	<0.005	0.003	0.0017	0.005	<0.002
Cured	0.024	0.44	<0.0005	<0.001	<0.002	<0.0002	0.005	<0.002

TABLE 19 (Cont'd)

Sample	As	Ba	Cd	Cr	Pb	Hg	Se	Ag
Spray-dryer product from baghouse - dolomite used as reagent - Strathmore Paper Co.								
Uncured	0.005	1.3	<0.0005	<0.005	0.003	0.001	0.006	<0.01
Cured	<0.003	0.39	0.0007	0.008	0.006	0.0005	0.011	<0.002
Spray-dryer product from spray-dryer hopper - recycle runs - research - Cottrell test facility - Comanche station								
Uncured	0.004	0.98	<0.01	0.065	<0.002	<0.0002	0.01	<0.01
Cured	<0.003	0.37	<0.0005	0.14	<0.002	0.0005	<0.008	0.24
Spray-dryer product from baghouse during recycle runs - research - Cottrell test facility - Comanche station								
Uncured	<0.003	8.0	<0.01	0.15	<0.002	0.0002	0.023	<0.01
Cured	<0.003	0.79	0.0006	0.007	<0.002	0.0006	<0.003	<0.002
Spray-dryer product from baghouse - recycle runs - Rockwell International's test facility - Joliet station (9:1 recycled product to fresh feed)								
Uncured	<0.003	1.0	0.0042	0.13	<0.002	0.0005	0.009	<0.01
Cured	<0.003	0.54	0.0009	0.024	<0.002	0.0007	<0.003	<0.002
9.4:1 recycled product to fresh feed								
Uncured	<0.003	1.0	0.0076	0.13	<0.002	0.0005	0.005	<0.01
Cured	<0.003	0.31	<0.0005	0.021	<0.002	0.0003	<0.003	<0.002
11.5:1 recycled product to fresh feed								
Uncured	<0.003	1.2	<0.0005	0.12	<0.002	0.0004	0.043	<0.01
Cured	<0.003	0.6	0.002	0.018	<0.002	0.0003	0.004	<0.002
Spray-dryer product from General Electric's test facility - Martin Drake station	<0.003	0.27	0.01	0.014	<0.002	<0.0002	0.02	<0.01
Spray-dryer product from baghouse - Joy/Niro test facility - Riverside station								
Uncured	<0.003	0.93	<0.0005	<0.005	<0.002	0.0017	0.01	<0.01
Cured	<0.003	0.47	<0.0005	0.011	<0.002	0.0003	<0.003	<0.002
Spray-dryer product from baghouse - Rockwell International's test facility - Sherburne County station								
Uncured	0.006	0.76	<0.0005	0.14	<0.002	<0.0002	<0.02	0.014
Cured	<0.003	0.52	0.0008	0.034	<0.002	0.0006	<0.003	<0.002
Cured	<0.003	0.26	<0.0005	0.053	<0.002	0.0003	0.007	<0.002

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Ref. 20.

TABLE 20 EP Tox Test Data for FGD Wastes, J.P. Woodyard, Stearns, Conrad, and Schmidt, Consulting Engineers, Inc. (mg/L, single and range values)

Element	RCRA Limit[a]	Lime Sludge (midwestern coal)	Lime Sludge (lignite)	Calcium-Based Dry-Scrubber Waste: Raw	Calcium-Based Dry-Scrubber Waste: Compacted
As	5.0	0.06	0.14	0.001-1.6	<0.001-0.03
Ba	100	1.6	<0.40	--	--
Cd	1.0	0.015	<0.025	0.001-1.5	<0.001-0.008
Cr	5.0	0.047	<0.10	--	--
Hg	0.2	0.002	<0.001	--	--
Pb	5.0	0.016	<0.50	--	--
Se	1.0	0.031	0.11	0.018	--
Ag	5.0	--	<0.06	--	--

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Sources: Data are from Refs. 23, 27, and 28.

TABLE 21 Ranges of EP Tox Test Values (mg/L, single and range values)

Element	RCRA Limit[a]	Unfixed	Fixed
As	5.0	<0.001-0.02	0.005
Cd	1.0	<0.001-0.005	<0.001-0.002
Se	1.0	0.005-0.008	<0.001-0.002

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 29

TABLE 22 EP Tox Test Data for FGD Wastes, J.E. Garlanger, Ardaman & Associates (mg/L)

Element	RCRA Limit[a]	Sample 1	Sample 2	Sample 3	Mean of Three Samples
As	5.0	0.010	0.0155	0.008	0.0112
Ba	100	0.150	0.235	0.240	0.208
Cd	1.0	0.012	0.0175	0.014	0.0145
Cr	5.0	0.053	0.048	0.056	0.052
Pb	5.0	0.001	<0.001	<0.001	<0.001
Hg	0.2	<0.0002	<0.0002	<0.0002	<0.0002
Se	1.0	0.015	0.0275	0.020	0.0208
Ag	5.0	<0.010	<0.010	<0.010	<0.010

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 24.

TABLE 23 EP Tox Test Data for FGD Wastes from the Arapahoe Power Plant, P. Winkler, Public Service Company of Colorado (mg/L; mean values, except for RCRA limit)

Element	RCRA Limit[a]	Reagent Na	Reagent Ca
As	5	0.09	<0.01
Ba	100	<0.005	<0.005
Cd	1	0.05	0.033
Cr	5	0.03	0.025
Pb	5	<0.002	<0.002
Hg	0.2	<0.001	<0.001
Se	1	0.29	0.08
Ag	5	0.005	<0.001

[a]100 times the maximum contaminant level (MCL) (Federal Register for 5/19/80).

Source: Data are from Ref. 25.

4 ORGANIC CONSTITUENTS OF FBC AND FGD SOLID WASTES

Studies addressing the concentrations of organic chemicals in FBC and FGD waste streams are relatively rare compared with studies addressing trace-element concentrations. Most organic analysis work on FBC systems has focused on airborne particulates and hydrocarbon emissions.[4,15] Similarly, limited data have been generated for FGD systems. Concentrations of organic compounds in FBC flue gas are presented in Table 24. These concentrations are compared to MATE* values for air; none are exceeded.

TABLE 24 Organic Compounds in FBC Flue Gas, K.S. Murthy, Battelle Columbus Laboratories

Substance	Concentration (ng/m^3) Flue Gas	Air MATE[a]
Anthracene/phenanthrene	53	483,000
Methyl anthracenes	5	483,000
Fluoranthene	26	90,000,000
Pyrene	9	233,000,000
Methylpyrene/fluoranthene	1.0	--
Benzo(c)phenanthrene	0.2	26,900,000
Chrysene/benz(a)anthracene	3.8	44,800
Benzofluoranthenes	1.0	897,000
Benz(a)pyrene	0.5	20
Hydrocarbons > C_6-C_{12} ($\mu g/m^3$)	1740	--
Hydrocarbons > C_{12} ($\mu g/m^3$)	58	--

[a]MATE = minimum acute toxicity effluent.

Source: Data are from Ref. 8

*Approximate concentrations of contaminants in air, water, or land effluents that may invoke minimal significant harmful responses to humans or the ecology within eight hours.

REFERENCES

1. Jackson, L., and F. Moore, *Analytical Aspects of the Fossil Energy Waste Sampling and Characterization Project*, U.S. Department of Energy, Morgantown Energy Technology Center, DOE/LC/00022-1599 (March 1984).

2. Thompson, C.M., *Chemical and Physical Characterization of Western Low-Rank Coal Waste Materials, Part 2: Byproducts from an Atmospheric Fluidized Bed Combustion System*, prepared by Radian Corp. for U.S. Department of Energy, Grand Forks Energy Technology Center, DOE/FC/10200-T3 (Nov. 1982).

3. Hall, R.R., et al., *Material Balance in Atmospheric Fluidized-Bed Combustion of North Dakota Lignite*, Proc. 7th International Conf. on Fluidized Bed Combustion, Grand Forks Energy Technology Center, DOE/FC-1004, CONF-821064-1 (1982).

4. Hanson, R.L., R.L. Carpenter, and G.J. Newton, *Chemical Characterization of Polynuclear Aromatic Hydrocarbons in Airborne Effluents from an Experimental Fluidized-Bed Combustor*, Proc. 4th International Symp. on Polynuclear Aromatic Hydrocarbons: Chemistry and Biological Effects (1979).

5. Sun, C.C., C.H. Peterson, and D.L. Keairns, *Experimental/Engineering Support for EPA's FPC Program, Final Report, Volume III: Solid Residue Study*, prepared by Westinghouse R&D Center for U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, EPA-600/7-80-015c (Jan. 1980).

6. Sun, C.C., and C.H. Peterson, *Fluidized-Bed Combustion Residue Disposal: Environmental Impact and Utilization*, Proc. 6th International Conf. on Fluidized-Bed Combustion, Vol. III: Technical Sessions, U.S. Department of Energy, CONF-800428, pp. 900-912 (Aug. 1980).

7. Fennelly, P.F., et al., *Preliminary Environmental Assessment of Coal-Fired Fluidized-Bed Combustion Systems*, prepared by GCA Corp. for U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, EPA-600/7-77-054 (May 1977).

8. Murthy, K.S., et al., *Multimedia Pollutant Emissions Data for Fluidized-Bed Combustion of Coal*, Proc. 5th International Conf. on Fluidized-Bed Combustion, Vol. II: Near-Term Implementation, U.S. Department of Energy, pp. 544-558 (Dec. 1977).

9. Grimshaw, T.W., et al., *Laboratory and Field Studies of Pressurized FBC Waste Leachate Generation and Attenuation*, Proc. 6th International Conf. on Fluidized-Bed Combustion, Vol. III: Technical Sessions, U.S. Department of Energy, CONF-800428, pp. 925-938 (Aug. 1980).

10. Grimshaw, T.W., et al., *Generation and Attenuation of Leachate from Fluidized-Bed Combustion of Solid Wastes: First Year Progress Report*, prepared by Radian Corp. for U.S. Environmental Protection Agency, EPA-600/7-80-095 (May 1980).

11. Minear, R.A., T.W. Grimshaw, and W.M. Little, *Assessment of Fluidized-Bed Combustion Solid Wastes for Land Disposal, Vol. 3: Appendices D and E*, prepared by Radian Corp. for U.S. Environmental Protection Agency, EPA/600/7-85/007c (Feb. 1985).

12. Eklund, A.G., and T.M. Wellington, *Composition and Leaching of FBC Wastes at the Alliance Test Facility*, prepared by Radian Corp. for the Electric Power Research Institute, CS-3715 (Nov. 1984).

13. Groenewold, G.H., and O.E. Manz, *Disposal of Fly Ash and Fly Ash Alkali FGD Waste in a Western Decoaled Strip Mine — Interim Report*, prepared for U.S. Department of Energy, Grand Forks Energy Technology Center (May 1982).

14. Thompson, C.M., *Chemical and Physical Characterization of Western Low-Rank Coal Waste Materials, Part 1: By-Products from Sodium-Based Dry-Scrubbing Systems*, prepared by Radian Corp. for U.S. Department of Energy, DOE/FC/10200-T2 (Aug. 1982).

15. Thompson, C.M., *Chemical and Physical Characterization of Western Low-Rank Coal Waste Materials, Part 3: Sludges from Wet Scrubbers Using Fly Ash as a Scrubbing Reagent*, prepared by Radian Corp. for U.S. Department of Energy, DOE/FC/10200-T4 (Dec. 1982).

16. Fling, R.B., et al., *Disposal of Flue Gas Cleaning Wastes: EPA Shawnee Field Evaluation — Third Annual Report*, prepared by Aerospace Corp. for U.S. Environmental Protection Agency, EPA-600/7-80-011 (Jan. 1980).

17. Rossoff, J., et al., *Disposal of By-Products from Nonregenerable Flue Gas Desulfurization Systems: Final Report*, prepared by Aerospace Corp. for U.S. Environmental Protection Agency, EPA-600/7-79-046 (Feb. 1979).

18. Santhanam, C.J., et al., *Full-Scale Field Evaluation of Waste Disposal from Coal-Fired Electric Generating Plants, Vol. 1: Sections 1-5*, prepared by Arthur D. Little, Inc., for U.S. Environmental Protection Agency, EPA-600/7-85-028a (June 1985).

19. Mohn, N.C., et al., *Environmental Effects of FGD Disposal, A Laboratory/Field Landfill Demonstration*, Proc. Symp. on Flue Gas Desulfurization, Vol. II, pp. 835-857 (March 1979).

20. Thompson, C.M., et al., *Characteristics of Waste Products from Dry-Scrubbing Systems*, prepared by Radian Corp. for Electric Power Research Institute, CS-2766, RP 1870-2 (Dec. 1982).

21. Coltharp, W.M., et al., *Review and Assessment of the Existing Data Base Regarding Flue Gas Cleaning Wastes*, prepared by Radian Corp. for Electric Power Research Institute, FP-671, Vol. 1, RP 786-2 (Jan. 1979).

22. Summers, K.V., G.L. Rupp, and S.A. Gherini, *Physical-Chemical Characteristics of Utility Solid Wastes*, prepared by Tetra Tech, Inc., for Electric Power Research Institute, EA-3236, RP 1487-12 (Sept. 1983).

23. *Recovery, Utilization, and Disposal of Solid By-Products Generated by Dry Flue Gas Desulfurization Systems: State of the Art and Research Needs*, prepared by Stearns, Conrad, and Schmidt, Consulting Engineers, Inc., for Electric Power Research Institute, SCS, CS-1765, RP 1260-16 (March 1981).

24. Garlanger, J.E., and T.S. Ingra, *Evaluation of Engineering Properties and Wet Stacking Disposal of Widows Creek FGD Gypsum Fly Ash Waste: Addendum I: EP Toxicity and Column Leaching Tests*, prepared by Ardaman & Associates for Tennessee Valley Authority, TVA/OP/EDT-84/23 (Dec. 1983).

25. Winkler, P., J.E. Wagner, and R.L. Pearson, *Disposal Characteristics of Dry Scrubber Waste*, prepared by Public Service Company of Colorado for Western Energy Supply and Transmission (WEST) Associates (May 1983).

26. *Analysis of Selected Trace Metals in Leachate from Selected Fossil Energy Materials, Phase II: Collaborative Test Program*, prepared by Engineering Science for U.S. Department of Energy and American Society for Testing and Materials, ASTM D19.12 (Jan. 1980).

27. Rose, S.J., et al., *Extraction Procedure and Utility Industry Solid Waste*, Electric Power Research Institute, EA-1667 (1981).

28. Bause, D.E., and K.T. McGregor, *Comparison of Four Leachate-Generation Procedures for Solid Waste Characterization in Environmental Assessment Programs*, U.S. Environmental Protection Agency, EPA-600/7-80-118 (1980).

29. Phillips, H.L., *An Evaluation of the Waste Product from a Calcium-Based Dry Flue Gas Desulfurization System*, thesis, University of Tennessee, Knoxville (June 1979).

APPENDIX A

FLUIDIZED-BED COMBUSTION — RESEARCH SUMMARIES

APPENDIX A

FLUIDIZED-BED COMBUSTION — RESEARCH SUMMARIES*

A.1 DOE-SPONSORED RESEARCH

The U.S. Department of Energy has sponsored studies of FBC solid waste leachate characteristics, mass-balance analysis of particulates, and organic analysis of particulates.[1,2,3,4] Table 1 summarizes these research efforts.

A.1.1 L. Jackson, Western Research Institute (Ref. 1)

One of the more comprehensive studies covering several emerging coal technologies, including FBC, was conducted by Jackson and Moore. A total of 94 wastes from 18 coal-fired power plants and from six emerging technologies was analyzed. The eight elements listed in RCRA were evaluated using the EP Tox test and the American Society for Testing and Materials (ASTM) leach test. As indicated in Table 1, no waste material would be classified as hazardous under the permissible levels (100 times the current drinking water standards) for the eight RCRA elements at the 95% confidence level. The two leaching procedures used for the 2492 leach tests on all the wastes yielded mean values for seven of the eight metals that were below 100 parts per billion (ppb), with most of them at 10 ppb or less. The exception to this pattern was barium, with values between 10 and 0.1 parts per million (ppm). However, this sample was not obtained from FBC waste. It was a fly ash sample obtained from an electrostatic precipitator. The raw data indicate that the value reported (160 mg/L) was five times higher than any other reported value. According to the authors, statistical analyses on this data point indicated that the value was an "outlier" and should be discarded. Table 3 summarizes the leachate data for the EP Tox test and the ASTM leach test.

A.1.2 C.M. Thompson, Radian Corporation (Ref. 2)

A study by Thompson of the characteristics of wastes from an atmospheric FBC system indicates that the concentrations of the eight RCRA elements were well below levels at which the wastes would be considered toxic. Fly ash wastes from four fuel feedstocks were analyzed by the EP Tox test. Two of the waste samples were obtained from combustion of North Dakota lignite; one of these sample runs included limestone in the feedstock. The third sample was derived from combustion of Texas lignite, and the fourth sample was obtained from combustion of Illinois subbituminous coal (with limestone added). The relatively high concentration of selenium in the leachate from the North Dakota lignite (with limestone) waste correlates with the high concentration found in the fly ash solids. The maximum concentration values obtained for arsenic and selenium were "markedly higher" in leachates from Texas lignite ash compared with the

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*The references cited in App. A are listed in Sec. A.3. The numbers do not correspond to those on pages 30-32.

other fly ashes. The author references a study by Thompson and Jones,[5] in which generally higher concentrations of selenium in conventional lignite fly ash leachates compared with western subbituminous coals were reported. The opposite was true for chromium concentrations -- that is, subbituminous fly ash leachate concentrations were higher than those from lignite. Adding limestone in the combustion of North Dakota lignite reduced the concentrations of boron and molybdenum in the leachates. Table 4 summarizes the results of the Thompson study. None of the mean values presented for the eight RCRA element concentrations exceed the RCRA limits.

The emissions and solid waste characteristics of pressurized FBC systems were evaluated by Chiu.[6] After reviewing data on solid waste leachates, he concludes that pressurized FBC system residues do not appear to be hazardous based on concentrations of measured trace metals not exceeding 100 times the National Interim Primary Drinking Water Standards. However, secondary drinking water standards for pH, total dissolved solids (TDS), and sulfate-ion concentrations may be exceeded. Magnesium concentrations were indicated to be a potential problem if dolomite were used as the sorbent material.

A.1.3 D.R. Sears, Grand Forks Energy Technology Center (Ref. 3)

A material-balance study by Hall et al. addressed trace- and minor-element concentrations of solid materials in the inlet and outlet streams of FBC systems. The authors conclude that a majority of the trace and minor elements exited in the primary cyclone catch (58% of the solid waste output) and the bed drain (38% of the solid waste output). Although this study did not address leachates, it did document the fact that FBC elemental emission rates are lower than those for conventional combustion and that the majority of trace-element constituents left the FBC system in the primary cyclone and bed drain.

A.1.4 J.J. Kovach, Morgantown Energy Technology Center (Ref. 4)

The Inhalation and Toxicology Research Institute collaborated with DOE's Morgantown Energy Technology Center (METC) to characterize the potential airborne particulate and hydrocarbon emissions from the METC atmospheric FBC system. Hanson et al. compared vapor-phase and particle-associated hydrocarbon concentration data for particulates from four experimental FBC systems. Similar polynuclear aromatic hydrocarbons (PAH) have been found in flue gas; some mutagenicity has been identified for suspended particles; and some PAH identified in FBC samples are known mutagens. The PAH associated with particulate emissions vary with fuel type, and the "highest concentrations and greatest variety of vapor-phase organics were found when Montana Rosebud subbituminous coal and Texas lignite were burned." The authors conclude that the "finding of mutagenic activity in extracts of particulate samples from FBC should serve as an indication of potential health risk" and that this finding should be put into perspective regarding the establishment of possible relationships between mutagenic activity and human exposure.

Hobbs et al.[7] assessed the potential toxicity and mutagenicity of effluents in laboratory animals. The inhalation of aerosols from the METC atmospheric FBC system was studied to determine the potential for producing respiratory disease and cancers. The highest vapor-phase organic concentrations in the stack effluent were obtained when Montana Rosebud subbituminous coal was burned. The vapor-phase organic concentrations, as well as the particle-associated hydrocarbon concentrations, were similar to those found in other atmospheric or pressurized FBC systems. The authors conclude that particle and trace-element emissions are similar to emissions from conventional power plants. Atmospheric FBC polycyclic organic emissions are higher than those from conventional power plants and are primarily vapors; however, the emissions are not mutagenic. Mutagenic activity has been detected in some bag-filter and stack-fly-ash samples.

A.2 EPA- AND EPRI-SPONSORED RESEARCH

The U.S. Environmental Protection Agency has funded research performed by the Westinghouse Research and Development Center,[8,9] GCA Corporation,[10] Battelle Columbus Laboratories,[11] and Radian Corporation.[12,13,14,15] The Westinghouse research effort involved determining the physical and chemical characteristics and leaching behavior of FBC spent sorbent and ash. The GCA Corporation study estimated the presence of organic compounds, trace elements, inorganic compounds, and particulates in FBC flue gas, solid wastes, and water discharges. The Battelle Columbus Laboratories' research involved comprehensive analysis of air pollutant emissions, solid residues, and leachates from solid waste. The Radian Corporation research included a laboratory and field study of leachate generation from FBC waste and attenuation by disposal media types. This last study included wastes obtained from the EPRI Babcock & Wilcox FBC unit. The EPRI-sponsored Radian Corporation study compared the data generated by the EPA-Radian study with new data collected following changes made to the EPRI Babcock & Wilcox FBC unit. Table 2 summarizes these research efforts.

A.2.1 D.L. Keairns, Westinghouse Research and Development Center (Refs. 8 and 9)

The Westinghouse Research and Development Center in Pittsburgh conducted research on FBC residue disposal and use. Seventeen waste leachate samples from eight FBC units were analyzed, and results were compared with drinking water standards and RCRA limits. The waste samples were derived from bed overflow material (partially reacted limestone or dolomite sorbent mixed with coal ash) and entrained material (fine particles of sorbent, char, and coal ash) collected at various parts of the particulate control system (cyclones and baghouses). Wastes were tested from pressurized and atmospheric FBC systems with once-through sorbent and regenerative sorbent.

Two tests developed by Westinghouse and the EP Tox test were used to generate leachates from the wastes. Westinghouse's continuous and intermittent shake tests are described as producing results that "are severer than conditions anticipated in actual land disposal."[8] The continuous shake test involves a 1:10 solid-to-liquid ratio and shaking the mixture for up to 400 hours. The intermittent test uses a 1:3 solid-to-liquid ratio and 10-15 cycles of 72-hour shaking. Samples were analyzed and a new leaching medium was added after each cycle. Deionized water, carbon-dioxide-saturated water (pH 4), and a sodium-acetate/acetic-acid buffer solution (pH 4.5) were used as the leaching media.

On the basis of the results from the EP Tox test, none of the eight RCRA elements exceeded the current limits. The highest average concentration was arsenic (0.94 ppm) obtained from a pressurized FBC unit with sorbent regeneration. Chromium was next highest, with average concentrations of 0.15-0.4 ppm obtained from three leachates extracted from bag filter, cyclone fines, and regenerator bed material. Table 5 contains EP Tox test results for the 17 waste samples analyzed. Results from the continuous 200-hour shake test are documented for individual FBC units by Sun et al.[8] Several trace-element levels were subjected to the shake test. Table 6 presents the results from the 200-hour shake test for bed and carryover material. Even though several trace-element levels were included in the test, only the eight RCRA elements are presented. The RCRA limits are provided for comparison purposes only.

Overall, none of the data indicate that trace-element levels will exceed the existing limits for the eight RCRA elements based on the Westinghouse 200-hour shake test, which the authors claim "project[s] the worst case" conditions in relation to actual land disposal. Results on other parameters indicate that "major concerns" for FBC residue disposal are the high pH, TDS, and sulfate and calcium levels in the leachate; thermal activity; and the large quantity of solid material needing disposal.[9]

A.2.2 P.F. Fennelly, GCA Corporation (Ref. 10)

The GCA Corporation study addressed the presence of organic compounds, trace elements, inorganic elements, and particulates in the flue gas, solid waste, and water discharge of FBC systems. Order-of-magnitude estimates were made of the parameters, based on available data. This study, completed in 1977, demonstrates that additional research is needed to acquire better data because the conclusions drawn are based on limited or estimated data. Thus, no significant information was available with regard to leachate generation. The research documentation, however, provides good descriptions of FBC systems.

A.2.3 K.S. Murthy, Battelle Columbus Laboratories (Ref. 11)

Solid waste leachate data were generated as part of a comprehensive study completed by Battelle Columbus Laboratories on the Exxon miniplant FBC unit. Nine waste streams were sampled, including leachates from spent-bed materials and a fly ash sample (second cyclone). An intermittent shake test was used to generate leachates. Fresh distilled water replaced the decanted leachate every 72 hours. The process was repeated 10 times. Leachates were analyzed for inorganic anions and organic compounds. No conclusive results were obtained from the organic analyses. However, according to the authors, the pH of the bed material leachate can be considered corrosive (i.e., pH > 12). Table 7 summarizes the inorganics analyzed for the bed material and fly ash. The RCRA limits for selenium, lead, and arsenic are provided for reference purposes only.

A.2.4 T.W. Grimshaw, Radian Corporation (Refs. 12, 13, and 14)

The EPA-sponsored study by Radian Corporation was a laboratory and field analysis of residue leachates from three FBC facilities. The laboratory investigation consisted of a multistep laboratory leaching protocol (batch equilibrium tests) to determine the leaching potential of solid residues and the attenuation capacity of disposal media. The laboratory protocol consisted of six steps (Fig. A.1): three steps to characterize the leaching behavior of one waste and three steps to determine the attenuation capacity of disposal media.[12] The extraction liquid was deionized water; extraction times ranged from 1-2 to 7 days; the solid-to-liquid mass ratio was 1:10; and all wastes were ground and agitated uniformly.[13]

A total of 17 field cells containing six disposal media (limestone, sandstone, shale, alluvium, interburden, and glacial till) and wastes from three FBC units (Babcock & Wilcox, Georgetown, and Exxon) were devised. These disposal media and wastes were physically and chemically analyzed.

The data for steps 1 and 4 of the protocol, presented in Table 8, allow comparisons of leachate derived from contact with fresh, deionized water, and of leachate exposed to fresh disposal media. The waste was obtained from the Exxon miniplant; the extraction time was seven days. Even though many parameters were tested, only selected parameters are listed. The eight RCRA elements are included with their limits for reference purposes only.

The RCRA extraction procedure was also used to evaluate the three FBC wastes. Table 9 presents the results from the tests and includes data from step 1 of the protocol to allow comparison between the two procedures. According to the data, none of the leachates exceed the RCRA limits based on the RCRA extraction procedure.[14]

A.2.5 A.G. Eklund, Radian Corporation (Ref. 15)

The EPRI-sponsored Radian study compared results obtained in 1983 with data obtained from the EPA-sponsored Radian study reviewed in Sec. A.2.4. The EPRI-sponsored Radian study focused on the EPRI Babcock & Wilcox facility and collected data concerning waste characterization following changes made to the facility. The leachate composition of the "EPRI waste" was obtained following the procedures specified in the EPA study. The RCRA EP Tox test was not used in the follow-up study. Step 1 of the batch equilibration protocol (Fig. A.1) was performed, and the results indicate that "elemental concentrations in the leachates were the same (within 99% confidence interval) for 15 species: aluminum, calcium, cadmium, cobalt, copper, iron, potassium, lithium, magnesium, manganese, nickel, silicon, titanium, vanadium, and zinc." Eight parameters (boron, barium, chromium, fluoride, sodium, sulfate, TDS, and total organic carbon [TOC]) were higher in concentration based on the EPRI study; in the EPA study, four parameters (chloride, molybdenum, strontium, and pH) had higher concentrations. Table 10 compares all parameters tested in the EPA- and EPRI-sponsored studies; RCRA limits are indicated for barium, cadmium, and chromium.

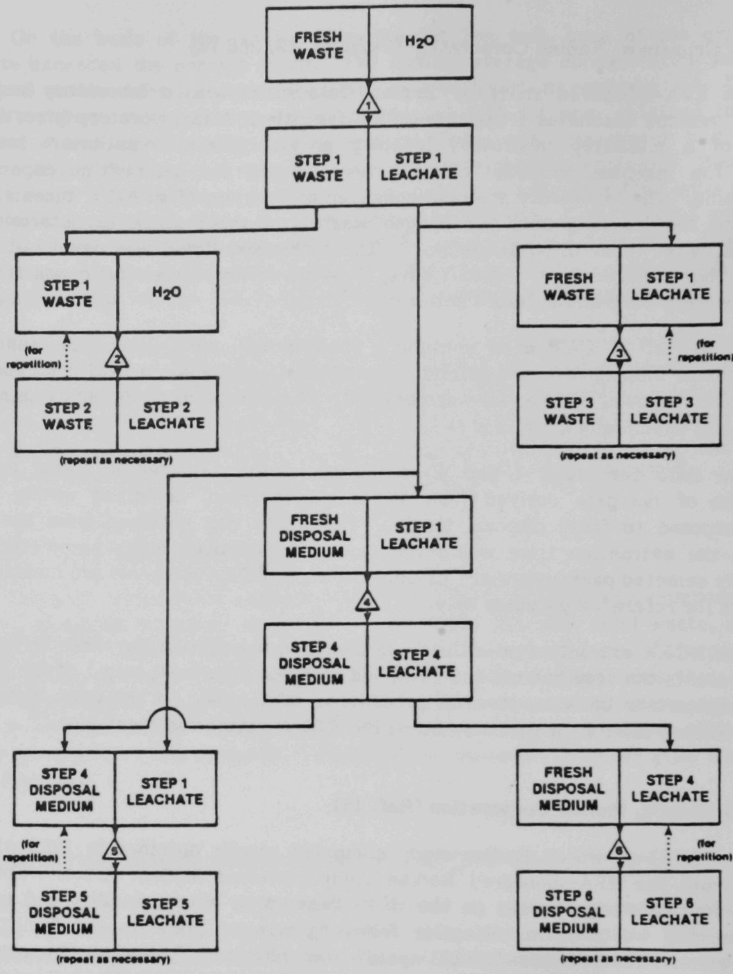

FIGURE A.1 Laboratory Batch Equilibration Protocol for FBC Leachate Generation and Attenuation (Source: Ref. 14)

A.3 REFERENCES CITED IN APPENDIX A

1. Jackson, L., and F. Moore, *Analytical Aspects of the Fossil Energy Waste Sampling and Characterization Project*, U.S. Department of Energy, Morgantown Energy Technology Center, DOE/LC/00022-1599 (March 1984).

2. Thompson, C.M., *Chemical and Physical Characterization of Western Low-Rank Coal Waste Materials, Part 2: Byproducts from an Atmospheric Fluidized Bed Combustion System*, prepared by Radian Corp., for U.S. Department of Energy, Grand Forks Energy Technology Center, DOE/FC/10200-T3 (Nov. 1982).

3. Hall, R.R., et al., *Material Balance in Atmospheric Fluidized-Bed Combustion of North Dakota Lignite*, Proc. 7th International Conf. on Fluidized Bed Combustion, Grand Forks Energy Technology Center, DOE/FC-1004, CONF-821064-1 (1982).

4. Hanson, R.L., R.L. Carpenter, and G.J. Newton, *Chemical Characterization of Polynuclear Aromatic Hydrocarbons in Airborne Effluents from an Experimental Fluidized-Bed Combustor*, Proc. 4th International Symp. on Polynuclear Aromatic Hydrocarbons: Chemistry and Biological Effects (1979).

5. Thompson, C.M., and B.F. Jones, *Determination of Hazardousness of Reuse Products Utilizing Low-Rank Western Coal Fly Ash/Bottom Ash*, prepared by Radian Corp., for U.S. Department of Energy, DOE/FC/10229-1 (Aug. 1981).

6. Chiu, S., *An Evaluation of the Environmental and Technical Aspects of Pressurized, Fluidized-Bed Combustors*, Argonne National Laboratory Report ANL/EES-TM-257 (Oct. 1983).

7. Hobbs, C.H., et al., *Physical, Chemical, and Biological Characterization of Atmospheric Pressure Fluidized-Bed Coal Combustion Effluents*, Proc. 6th International Conf. on Fluidized-Bed Combustion, Vol. III: Technical Sessions, U.S. Department of Energy, CONF-800428, pp. 1274-1282 (Aug. 1980).

8. Sun, C.C., C.H. Peterson, and D.L. Keairns, *Experimental/Engineering Support for EPA's FPC Program; Final Report, Volume III: Solid Residue Study*, prepared by Westinghouse R&D Center for U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, EPA-600/7-80-015c (Jan. 1980).

9. Sun, C.C., and C.H. Peterson, *Fluidized-Bed Combustion Residue Disposal: Environmental Impact and Utilization*, Proc. 6th International Conf. on Fluidized-Bed Combustion, Vol. III: Technical Sessions, U.S. Department of Energy, CONF-800428, pp. 900-912 (Aug. 1980).

10. Fennelly, P.F., et al., *Preliminary Environmental Assessment of Coal-Fired Fluidized-Bed Combustion Systems*, prepared by GCA Corp. for U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, EPA-600/7-77-054 (May 1977).

11. Murthy, K.S., et al., *Multimedia Pollutant Emissions Data for Fluidized-Bed Combustion of Coal*, Proc. 5th International Conf. on Fluidized-Bed Combustion, Vol. II: Near-Term Implementation, U.S. Department of Energy, pp. 544-558 (Dec. 1977).

12. Grimshaw, T.W., et al., *Laboratory and Field Studies of Pressurized FBC Waste Leachate Generation and Attenuation*, Proc. 6th International Conf. on Fluidized-Bed Combustion, Vol. III: Technical Sessions, U.S. Department of Energy, CONF-800428, pp. 925-938 (Aug. 1980).

13. Grimshaw, T.W., et al., *Generation and Attenuation of Leachate from Fluidized-Bed Combustion of Solid Wastes: First Year Progress Report*, prepared by Radian Corp. for U.S. Environmental Protection Agency, EPA-600/7-80-095 (May 1980).

14. Minear, R.A., T.W. Grimshaw, and W.M. Little, *Assessment of Fluidized-Bed Combustion Solid Wastes for Land Disposal, Vol. 3: Appendices D and E*, prepared by Radian Corp. for U.S. Environmental Protection Agency, EPA/600/7-85/007c (Feb. 1985).

15. Eklund, A.G., and T.M. Wellington, *Composition and Leaching of FBC Wastes at the Alliance Test Facility*, prepared by Radian Corp. for the Electric Power Research Institute, CS-3715 (Nov. 1984).

APPENDIX B

FLUE-GAS DESULFURIZATION — RESEARCH SUMMARIES

APPENDIX B

FLUE-GAS DESULFURIZATION — RESEARCH SUMMARIES*

B.1 DOE-SPONSORED RESEARCH

The several studies sponsored by the U.S. Department of Energy to characterize leachates from wastes produced by FGD systems (Table 11) are summarized below. L. Jackson, Western Research Institute;[1] G.H. Groenewold, University of North Dakota;[2] and C.M. Thompson, Radian Corporation.[3,4] Table 11 summarizes these research efforts. Studies completed by L.E. Wangen and M.M. Jones, Los Alamos National Laboratory[5] and by R.D. Doctor[6] and J.L. Gillette and S. Chiu[7] at Argonne National Laboratory were also identified in the data base searches.

B.1.1 L. Jackson, Western Research Institute (Ref. 1)

In the Western Research Institute study, the following three scrubber sludge wastes were analyzed: a sludge generated from lignite combustion at a North Dakota power station, a sludge generated from bituminous coal burned at a Pittsburgh power station, and the same bituminous coal scrubber sludge fixed with a 10% addition of lime by weight. Table 15 presents the results of the three scrubber sludge samples using the RCRA EP Tox test. The data show that no scrubber sludge leachate exceeded the RCRA limits.

B.1.2 G.H. Groenewold, University of North Dakota (Ref. 2)

In the University of North Dakota study of FGD wastes from the Milton Young power station in North Dakota, very alkaline fly ash was used as a substitute for lime or limestone to react with the sulfur dioxide in the flue gas. The fly ash was derived from the plant's electrostatic precipitators. The study addressed the effects on groundwater of disposing of fly ash and FGD wastes. On the basis of data obtained from piezometers installed within the waste disposal areas and in undisturbed areas adjacent to the site, the authors conclude that "neither the fly ash nor the fly ash FGD waste ... constitutes a hazardous waste as defined by RCRA regulations." However, the authors also indicate that the wastes in contact with water are "characterized by very high TDS concentrations" and that "sulfate, lead, and chromium concentrations are sufficiently high so that the water would be unfit to drink." The wastes "may have the potential to degrade subsurface water with respect to molybdenum."

*The references cited in App. B are listed in Sec. B.5. The numbers do not correspond to those on pages 30-32.

B.1.3 C.M. Thompson, Radian Corporation (Refs. 3 and 4)

Radian Corporation investigated both dry-[3] and wet-scrubbing[4] systems; the studies are summarized separately in Table 11. The dry system involves dry injection of sodium salts into the flue gas and use of spray dryers as gas-reagent-contacting systems. The wet system uses alkaline fly ash as the FGD reagent. In both cases, wastes were subjected to the EP Tox test procedure.

Five waste samples from dry-scrubbing processes were examined for the eight RCRA trace elements in EP Tox test extracts. One sample was from a spray-drying system, and the other four were from dry-injection systems. Concentrations of the eight RCRA trace elements for the extracts from the five wastes are provided in Table 16. Note that the type of coal burned and sorbent type are indicated for each system. None of the concentrations exceed the levels at which a waste would be considered toxic under current RCRA limits.

In the wet-scrubber study, samples of untreated sludge were obtained from four power stations. Fly ash and lime, fly ash from an electrostatic precipitator, fly ash from flue gas, and limestone were the scrubber reagents. The EP Tox test was used to obtain extract concentration levels for the eight RCRA elements for the untreated sludge samples (Table 17). Sludges from two of the plants (M.R. Young and Shawnee) were subjected to different treatment processes and EP extracts were obtained. Overall, treated sludge from the M.R. Young plant exhibited concentrations that were significantly lower compared with untreated sludge for most of the 21 elements measured. Similar results were obtained from the Shawnee sludge, but with some exceptions noted. Overall, however, concentrations were below RCRA limits for all treated-sludge EP extracts.

B.1.4 L.E. Wangen, Los Alamos National Laboratory (Ref. 5)

Solid wastes (solid materials and 24 liquid samples) from eight power plants using wet FGD scrubbers were analyzed. Data were collected for 21 trace elements, and concentrations obtained from power plants burning high-sulfur eastern coal and low-sulfur western coal were compared. The authors conclude that "concentrations are generally lower in liquors from eastern plants, with the exception of arsenic and molybdenum." Differences in liquor pH, coal composition, or scrubber process used are indicated as the likely cause for the differences.

B.1.5 R.D. Doctor and J.L. Gillette, Argonne National Laboratory (Refs. 6 and 7)

The authors reviewed FGD technologies, but focused on process descriptions, environmental effects, and economic considerations. No specific data were reported concerning leachate characteristics of FGD wastes.

B.2 EPA-SPONSORED RESEARCH

The U.S. Environmental Protection Agency sponsored two studies by Aerospace Corporation; both assessed disposal techniques for FGD wastes and collected waste leachate data.[8,9] Arthur D. Little, Inc., conducted a field study of six FGD waste disposal sites, and leachate data from two scrubber sludge samples were documented.[10] The Combustion Engineering, Inc., and Louisville Gas & Electric research effort also addressed leachate characteristics based on monitoring of FGD disposal sites.[11] Table 12 summarizes these programs. The previously discussed research program by Westinghouse (Sec. A.2.1) compared leachate data from FBC residues with three FGD sludge samples.

B.2.1 R.B. Fling, Aerospace Corporation (Ref. 8)

Sludges generated from two scrubbers using lime and limestone absorbents were evaluated. Eight disposal ponds were used at the Shawnee steam plant in Paducah, Ky. Two of the ponds contained untreated sludges, three contained sludges that were chemically treated, and three contained untreated sludges with underdrainage. All of the ponds contained 40% by weight fly ash. Leachate was collected from all ponds, and the authors conclude that there was "no effect attributable to chemically treated or untreated waste disposal" in the eight ponds. On the basis of several thousand analyses of treated and untreated sludge leachates, trace-element concentrations greater than 10 times the drinking water standards in effect at the time of the study were obtained in only two instances: one selenium and one cadmium concentration were 10-20 times the allowable standard.

B.2.2 J. Rossoff, Aerospace Corporation (Ref. 9)

Leachate was collected by filtering excess liquor and supernate from approximately 1 L of sludge (50% solids). Deionized water was added to the solids, and aliquots were collected based on pore-volume displacements. Initially, leachate concentrations were obtained until 50 pore volumes had been displaced. Ninety percent of the decrease in leachate parameters was observed after three pore volumes had been displaced. Therefore, the number of pore volumes displaced was reduced to 10. Samples of sludge liquor and leachates from three power stations (Shawnee, Paddy's Run, and Plant Scholz) were analyzed with and without fly ash included. The authors conclude from the data that fly ash mixed with sludge will raise the concentrations of only a few trace elements compared with sludge not mixed with fly ash.

B.2.3 C.J. Santhanam, Arthur D. Little, Inc. (Ref. 10)

Six ash and FGD waste disposal sites were evaluated in the study by A.D. Little, Inc. Two of the sites (Elrama plant in Pennsylvania and Sherburne County plant in Minnesota) included disposal of stabilized FGD waste and combined fly-ash/FGD waste. Three FGD samples were obtained, and the RCRA EP Tox test was applied. Concentrations of the eight RCRA elements were documented based on the results for the three

FGD sludge grab samples analyzed (Table 18). Also included in the table are data referenced in the A.D. Little report that show concentration ranges of the eight RCRA elements for samples analyzed by Engineering Science.[12] Ranges of concentrations are presented and, except for selenium, none of the trace-metal levels exceed the RCRA limits. The wastes that exceed the selenium limit are treated and untreated bituminous scrubber sludges from the Elrama power station in Pittsburgh. Nine samples were analyzed from the treated scrubber sludge, and eight samples were analyzed for the untreated sludge.

B.2.4 N.C. Mohn, Combustion Engineering, Inc., and R.P. Van Ness, Louisville Gas & Electric (Ref. 11)

Leachates from wet FGD sludges from the Paddy's Run station were analyzed both in the laboratory and in the field. In the laboratory analysis, the sludges were evaluated with various degrees of dewatering, fly-ash mixing, and additions of lime. Column-leaching tests of three mixes were performed. In the field study, leachates were collected from small- and large-scale impoundments containing various proportions of sludge, lime, and moisture. Leachate concentrations from the large impoundments generally decreased with depth and time in cases where sufficient long-term samples were analyzed. On the basis of the RCRA limits in effect (10 times the maximum contaminant level) in 1979, all leachate concentrations were below RCRA levels; the exceptions were two instances where cadmium, and one instance where selenium, exceeded the 1979 limits. It could not be determined whether the current limits had been exceeded. Generally higher concentrations of leachate were found in the smaller impoundments because soil and vegetation were not established there.

B.3 EPRI-SPONSORED RESEARCH

The Electric Power Research Institute has sponsored research projects concerning many facets of the solid waste generated by fossil-fueled power plants. Five reports present information on various FGD processes and their waste streams. Radian Corporation performed two of these projects: the first characterized waste products from dry-scrubbing systems[13] and the second reviewed the existing data base on flue-gas-cleaning wastes.[14] The third report reviewed in this section was prepared by Tetra Tech, Inc., and is a compilation of existing data on the physical and chemical characteristics of utility solid wastes.[15] Stearns, Conrad, and Schmidt, Consulting Engineers, Inc., prepared a report dealing with dry FGD systems. The concepts of recovery and use of by-products from these systems are discussed.[16] The last of the reports reviewed was prepared by Fred C. Hart & Associates. This report was initiated in response to the passage of RCRA in 1976 and dealt with the impact on utilities if solid wastes from their power plants were classified as hazardous.[17] All of these studies, with the exception of the Fred C. Hart study, are summarized in Table 13. Each of these research projects was sponsored by different EPRI project managers from various divisions.

B.3.1 C.M. Thompson, Radian Corporation (Ref. 13)

This Radian Corporation study was the first independent evaluation of samples from a wide range of supplier systems scrubbing sulfur dioxide from utility flue gas. At the time this project was undertaken, most of the information available had been provided by the vendors of the various systems, and no comparative studies had been performed. Eighteen samples representing nine test facilities that used dry FGD systems were collected and sent to EPRI for analysis. This study is the only one of the EPRI-sponsored studies that generated baseline data. The facilities embraced a range of site locales, operating capacities, coal origins, and scrubbing systems. The scrubbing reagents used at these facilities included lime, nahcolite, sodium carbonate, and calcined dolomite. The FGD processes worked by dry injection of sodium salts or by contact of the reagent and the flue gas in a spray dryer. Dry-scrubbing waste products contained fly ash, products of the desulfurization reaction (sodium sulfite and sodium sulfate or calcium sulfite and calcium sulfate), unused reagent (sodium carbonate or calcium hydroxide), and products of side reactions (calcium carbonate).

The EP Tox test and an extraction that is identical to it, except that acetic acid is not used to adjust the pH, were performed. Both of these extraction procedures were carried out on cured and uncured waste samples. The curing used involved mixing the waste with water, compacting it, and aging it for four weeks at high relative humidity at room temperature. Leachates from the extractions were analyzed for the eight RCRA elements plus 20 others. The data on the RCRA elements indicate that none of the samples exceeded the RCRA limits (Table 19). A brief description of the facility that generated the waste is included in the table. Duplicate analyses were performed on two of the samples. The elemental concentrations tended to be lower in extracts of samples that had been cured. All of the waste products tested would be classified as nontoxic according to the RCRA guidelines for metal toxicity; thus, the wastes qualify for a nonhazardous classification.

B.3.2 W.M. Coltharp, Radian Corporation (Ref. 14)

The existing data base as of mid-1977 regarding FGD sludge and fly ash was reviewed. At the time the report was written, very few data were available on the composition of sludge and ash leachates. No methodology had been established for extraction procedures, and no maximum contamination levels had been set for comparison purposes. The data published in the report include analyses performed on leachates obtained through laboratory leaching techniques, field leaching, laboratory soil attenuation, and field soil attenuation. Seventy-four elements were analyzed by spark-source mass spectroscopy. Because the methodology was not consistent in any of these studies, the data are not presented here. The results were compared with the National Interim Primary Drinking Water Requirements and the EPA Recommended Secondary Constituent Levels.

B.3.3 K.V. Summers, Tetra Tech, Inc. (Ref. 15)

Tetra Tech, Inc., searched for published data on the physical and chemical characteristics of utility solid wastes. Its main objective was to obtain available information on each of the various technologies and to delineate any discernable trends. Another task was to investigate the various analytical techniques employed in an effort to establish guidelines for the most appropriate method. The report covered the various fossil-fueled electricity-generating technologies; therefore, information dealing with leachates from FGD processes constitutes a small fraction of the report. Data are presented on two different lime sludges from wet FGD processes using different types of coal. Data from a dry calcium-based scrubber waste in its raw and compacted forms are also included. The results of the EP Tox test extractions are presented in Table 20. Also covered in the report is the definition of the two general methods of sludge processing used in conjunction with wet FGD systems: stabilization and fixation. Stabilization involves blending the sludge with another substance, resulting in the alteration of its physical properties. Fixation involves treating the sludge with additional substances that induce chemical reactions.

B.3.4 J.P. Woodyard, Stearns, Conrad, and Schmidt, Consulting Engineers, Inc. (Ref. 16)

This project was also a review of the existing information on dry FGD waste products, with an emphasis on dry-injection and spray-dryer systems. The report also includes information on waste characteristics, recovery, reuse, utilization, and disposal of wastes from dry FGD processes. No information on leachate from either uncompacted or compacted sodium-based wastes was available, so the data presented in Table 21 were derived from leaching fixed and unfixed calcium-based dry FGD waste. Three extraction procedures were employed in the analysis of this waste, but only the results from EP Tox test procedure are included.

The calcium-based waste was fixed by compaction in the presence of water. In all cases examined, fixed specimen extracts showed lower metal content than the unfixed specimens. These tests revealed that the wastes examined would not be classified as hazardous under RCRA regulations and that fixation appears to be an effective means of preventing the release of metals. When attempting to establish trends in the waste streams from FGD processes, one should consider whether the reagent used is calcium- or sodium-based. Because sodium compounds are approximately 100 times more soluble in water than calcium compounds, the sodium-based wastes will probably have a greater tendency to leach, requiring additional attention prior to disposal.

B.3.5 F.C. Hart, Fred C. Hart, Associates, Inc. (Ref. 17)

The Resource Conservation and Recovery Act of 1976 created federal and state regulatory authority over both solid and hazardous wastes. Fred C. Hart Associates, Inc., assembled data from published and industry documents in an effort to assess the effect of RCRA on utilities. Waste streams from all fossil-fueled power plants were investigated to determine the potential for the waste to be classified as hazardous under

RCRA. The analytical data dealing with FGD waste were very limited and not well defined; therefore, these data are not included in this report.

B.4 TVA- AND WEST-ASSOCIATES-SPONSORED RESEARCH

The two research programs sponsored by TVA[18] and WEST Associates,[19] both of which analyzed FGD wastes using the EP Tox text, are summarized in Table 14.

B.4.1 J.E. Garlanger, Ardaman & Associates (Ref. 18)

This research effort examined FGD gypsum/fly-ash waste produced at the Widows Creek power station. Three samples of waste were subjected to the EP Tox test and a column leaching test. The former showed that the "Widows Creek FGD gypsum-fly ash waste was found to lack the characteristics of EP toxicity." Table 22 presents data from the three FGD samples subjected to the EP Tox test.

B.4.2 P. Winkler, Public Service Company of Colorado (Ref. 19)

The chemical characteristics of wastes from dry-scrubbing systems were analyzed. Waste samples were obtained from an experimental spray dryer (EPRI Particulate Test Control Facility, Arapahoe steam-electric power plant) and from a dry-sodium injection system (Cameo steam-electric station, Grand Junction, Colo.). All samples were combined with fly ash and analyzed using the EP Tox test. The results from this testing show that the concentrations of the eight RCRA elements did not exceed the RCRA limits. Table 23 summarizes the waste leachate concentrations obtained for both sodium- and calcium-based reagents from the Arapahoe plant.

B.5 REFERENCES CITED IN APPENDIX B

1. Jackson, L., and F. Moore, *Analytical Aspects of the Fossil Energy Waste Sampling and Characterization Project*, U.S. Department of Energy, Morgantown Energy Technology Center, DOE/LC/00022-1599 (March 1984).

2. Groenewold, G.H., and O.E. Manz, *Disposal of Fly Ash and Fly Ash Alkali FGD Waste in a Western Decoaled Strip Mine — Interim Report*, prepared for U.S. Department of Energy, Grand Forks Energy Technology Center (May 1982).

3. Thompson, C.M., *Chemical and Physical Characterization of Western Low-Rank Coal Waste Materials, Part 1: By-Products from Sodium-Based Dry-Scrubbing Systems*, prepared by Radian Corp. for U.S. Department of Energy, DOE/FC/10200-T2 (Aug. 1982).

4. Thompson, C.M., *Chemical and Physical Characterization of Western Low-Rank Coal Waste Materials, Part 3: Sludges from Wet Scrubbers Using Fly Ash as a Scrubbing Reagent*, prepared by Radian Corp. for U.S. Department of Energy, DOE/FC/10200-T4 (Dec. 1982).

5. Wangen, L.E., and M.M. Jones, *Chemical Element Concentrations in Liquids and Solids Associated with Power Plants Using FGD Systems*, Los Alamos National Laboratory Report LA-8929-MS (Aug. 1981).

6. Doctor, R.D., *Utility Flue-Gas Desulfurization: Innovations and System Availability*, Argonne National Laboratory Report ANL/ECT-11 (March 1982).

7. Gillette, J.L., and S. Chiu, *Flue-Gas Desulfurization: Review of Selected Commercial and Advanced Technologies*, Argonne National Laboratory Report ANL/FE-81-51 (Feb. 1981).

8. Fling, R.B., et al., *Disposal of Flue Gas Cleaning Wastes: EPA Shawnee Field Evaluation — Third Annual Report*, prepared by Aerospace Corp. for U.S. Environmental Protection Agency, EPA-600/7-80-011 (Jan. 1980).

9. Rossoff, J., et al., *Disposal of By-Products from Nonregenerable Flue Gas Desulfurization Systems: Final Report*, prepared by Aerospace Corp. for U.S. Environmental Protection Agency, EPA-600/7-79-046 (Feb. 1979).

10. Santhanam, C.J., et al., *Full-Scale Field Evaluation of Waste Disposal from Coal-Fired Electric Generating Plants*, Vol. 1: Sections 1-5, prepared by Arthur D. Little, Inc., for U.S. Environmental Protection Agency, EPA-600/7-85-028a (June 1985).

11. Mohn, N.C., et al., *Environmental Effects of FGD Disposal, A Laboratory/Field Landfill Demonstration*, Proc. Symp. on Flue Gas Desulfurization, Vol. II, pp. 835-857 (March 1979).

12. *Analysis of Selected Trace Metals in Leachate from Selected Fossil Energy Materials, Phase II: Collaborative Test Program*, prepared by Engineering Science for U.S. Department of Energy and American Society for Testing and Materials, ASTM D19.12 (Jan. 1980).

13. Thompson, C.M., et al., *Characteristics of Waste Products from Dry-Scrubbing Systems*, prepared by Radian Corp. for Electric Power Research Institute, CS-2766, RP 1870-2 (Dec. 1982).

14. Coltharp, W.M., et al., *Review and Assessment of the Existing Data Base Regarding Flue Gas Cleaning Wastes*, prepared by Radian Corp. for Electric Power Research Institute, FP-671, Vol. 1, RP 786-2 (Jan. 1979).

15. Summers, K.V., G.L. Rupp, and S.A. Gherini, *Physical-Chemical Characteristics of Utility Solid Wastes*, prepared by Tetra Tech, Inc., for Electric Power Research Institute, EA-3236, RP 1487-12 (Sept. 1983).

16. *Recovery, Utilization, and Disposal of Solid By-Products Generated by Dry Flue Gas Desulfurization Systems: State of the Art and Research Needs*, prepared by Stearns, Conrad, and Schmidt, Consulting Engineers, Inc., for Electric Power Research Institute, SCS, CS-1765, RP 1260-16 (March 1981).

17. Hart, F.C., and B.T. DeLaney, *The Impact of RCRA (PL 94-580) on Utility Solid Wastes*, Fred C. Hart Associates, Inc., FP-878, TPS 78-779 (Aug. 1978).

18. Garlanger, J.E., and T.S. Ingra, *Evaluation of Engineering Properties and Wet Stacking Disposal of Widows Creek FGD Gypsum Fly Ash Waste: Addendum I: EP Toxicity and Column Leaching Tests*, prepared by Ardaman & Associates for Tennessee Valley Authority, TVA/OP/EDT-84/23 (Dec. 1983).

19. Winkler, P., J.E. Wagner, and R.L. Pearson, *Disposal Characteristics of Dry Scrubber Waste*, prepared by Public Service Company of Colorado for Western Energy Supply and Transmission (WEST) Associates (May 1983).

APPENDIX C

ORGANIC CONSTITUENTS OF FBC AND FGD SOLID WASTES — RESEARCH SUMMARIES

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Sun et al.[1] compared FBC leachates and FGD leachates and liquors, and addressed qualitatively TOC concentrations. Concentrations are not provided for individual organic compounds, and TOC is simply reported as "low" for leachates and liquors obtained from FBC and FGD systems. Thompson et al.[2] conclude that for FGD dry-scrubbing systems, "no pesticides are expected"; thus, analysis for the six RCRA pesticides was not considered necessary.

Fennelly et al.[3] assessed FBC residues. They estimate that the concentration of PAH in FBC flue gas is about 1 ppb. They conclude that PAH concentrations "should not be high enough to cause problems."

An assessment of FBC residues by Henschel[4] indicates that analyzing for the chlorinated organic pesticides and herbicides listed in the proposed Federal Register guidelines of December 18, 1978, is unnecessary.

Thompson[5] did not address organic compounds in his study of FBC residues. He concludes that incomplete combustion of coal resulting from abnormal system operation would require investigation of leachable organics from the incompletely burned samples.

The EPA-sponsored study by Grimshaw et al.[6] and the EPRI-sponsored study by Eklund and Wellington[7] include TOC data for leachates. Values range from 1.1 mg/L for leachate generated from step 1 of the lab protocol (Fig. A.1) to an average of 3.4 mg/L based on attenuation by disposal media.[8] The TOC concentrations from the Eklund and Wellington study averaged 40 mg/L.[7] No TOC concentration limits exist; thus, conclusions cannot be drawn regarding the effect of these concentration levels.

In Murthy et al.,[9] concentrations of polycyclic organic matter in FBC flue gas (Table 24) and bed reject solids were addressed. The authors state that no environmental problems for land disposal should result, based on the data obtained. No conclusive results were available to determine which organic compounds in bed reject leachates were present in harmful amounts.

REFERENCES CITED IN APPENDIX C

1. Sun, C.C., C.H. Peterson, and D.L. Keairns, *Environmental Impact of the Disposal of Processed and Unprocessed FBC Bed Material and Carry-Over*, Proc. 5th International Conf. on Fluidized-Bed Combustion, Vol. II, pp. 846-873 (Dec. 1977).

2. Thompson, C.M., et al., *Characteristics of Waste Products from Dry-Scrubbing Systems*, prepared by Radian Corp. for Electric Power Research Institute, CS-2766, RP 1870-2 (Dec. 1982).

3. Fennelly, P.F., et al., *Preliminary Environmental Assessment of Coal-Fired Fluidized-Bed Combustion*, Proc. 4th International Conf. on Fluidized-Bed Combustion, U.S. Energy Research and Development Administration, pp. 475-491 (Dec. 1975).

4. Henschel, D.B., *Assessment of Fluidized-Bed Combustion Residues*, U.S. Environmental Protection Agency (Oct. 1979).

5. Thompson, C.M., *Chemical and Physical Characterization of Western Low-Rank Coal Waste Materials, Part 2: Byproducts from an Atmospheric Fluidized Bed Combustion System*, prepared by Radian Corp. for U.S. Department of Energy, Grand Forks Energy Technology Center, DOE/FC/10200-T3 (Nov. 1982).

6. Grimshaw, T.W., et al., *Generation and Attenuation of Leachate from Fluidized-Bed Combustion of Solid Wastes: First Year Progress Report*, prepared by Radian Corp. for U.S. Environmental Protection Agency, EPA-600/7-80-095 (May 1980).

7. Eklund, A.G., and T.M. Wellington, *Composition and Leaching of FBC Wastes at the Alliance Test Facility*, prepared by Radian Corp. for the Electric Power Research Institute, CS-3715 (Nov. 1984).

8. Groenewold, G.H., and O.E. Manz, *Disposal of Fly Ash and Fly Ash Alkali FGD Waste in a Western Decoaled Strip Mine — Interim Report*, prepared for U.S. Department of Energy, Grand Forks Energy Technology Center (May 1982).

9. Murthy, K.S., et al., *Multimedia Pollutant Emissions Data for Fluidized-Bed Combustion of Coal*, Proc. 5th International Conf. on Fluidized-Bed Combustion, Vol. II: Near-Term Implementation, U.S. Department of Energy, pp. 544-558 (Dec. 1977).